Distance: A framework for improving spatial cognition within digital architectural models

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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B.Arch

B.BSc

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August 2014

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2015

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I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work that has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and ethics procedures and guidelines have been followed.

Antony W. Pelosi
August 2015

Abstract

In this exegesis, I investigate the need for improvements to navigation tools and locational awareness within digital architectural models so that users' spatial cognition can be enhanced.

Evidence shows that navigation and disorientation are common problems within digital architectural models, often impairing spatial cognition. When a designer or contractor explores a completed digital architectural model for the first time, it can be a progressively frustrating experience, often leading to the creation of an incorrect cognitive map of the building design.

In this exegesis, I use a reflective practice research method across three project-based design investigations. I draw on aspects of architectural communication, digital interaction, and spatial cognition. The first investigation, Translation projects, explores the transformation of two-dimensional drawing conventions into three-dimensional interactive digital models, exposing the need for improved navigation and wayfinding. The second investigation, a series of artificial intelligence navigation projects, explores navigation methods to aid spatial cognition by providing tools that help to visualise the navigation process, paths to travel, and paths travelled. The third and final investigation, Distance projects, demonstrates the benefits of productive transition in the creation of cognitive maps. During the transition, assistance is given to aid the estimation of distance.

The original contribution to knowledge that this research establishes is a framework for navigation tools and wayshowing strategies for improving spatial cognition within digital architectural models. The consideration of wayshowing methods, focusing on spatial transitions beyond predefined views of the digital model, provides a strong method for aiding users to construct comprehensive cognitive maps. This research addresses the undeveloped field of aiding distance estimation inside digital architectural models. I argue that there is a need to improve spatial cognition by understanding distance, detail, data, and design when reviewing digital architectural models.

Acknowledgements

This has been an extended journey of exploration and discovery, often finding myself in different whiteout conditions.

I will always be exceptionally thankful for Mark Burry and Jane Burry's ever-timely supervision in navigating me through my research, allowing me to get lost, always there to guide me forward.

I am grateful for Russell Lowe's encouragement and vision.

I thank Oliver Blair without whom many of the projects would not have been possible.

I am thankful to the many people who have critiqued my research at RMIT's Graduate Research Conference and Practice Research Symposium: Guillermo Aranda Mena, Andrew Brennan, Margot Brereton, Andrew Burrow, Nancy Cheng, Paul Coats, Tom Daniell, Jill Franz, John Frazer, Ken Friedman, Ranulph Glanville, Lawrence Harvey, Dominik Holzer, Jeff Malpas, Jules Moloney, Susu Nousala, Michael Ostwald, Juliette Peers, Claus Peder Pedersen, Flora Salim, Charles Rice, Alex Selenitsch, Mark Taylor, and Suzette Worden, and also including all the fellow SIAL PhD candidates I have met during this journey.

Julieanna Preston for her on-going supportive scholarly advice.

I also thank my colleagues and friends Anna Brown, Rodney Adank, Stuart Foster, Dorrita Hanna h, Nick Kapica, Anne Noble, and Amanda Yates.

Professional editor, Mark Tippett of Earth Research, provided copyediting and proofreading services in accordance with the guidelines laid out in the university-endorsed national guidelines for editing research theses.

To my sons Max and Dylan, who have only ever known me while I have been on this journey.

Contents

Figure 1.0
Antarctica: The Grain of White #8, in which Anne Noble (2009) demonstrates whiteout conditions, a merging of white surfaces with a lack of both scale and distance clues.

Document Layout Design:

This exegesis has been designed with the body text running as a continuous stream on the right-hand page only, supported by figures intermittently on the left-hand page only, both page types are numbered.

1 Introduction

Orienting location

Forecast
White inside the weather,
white shadow, white shine:
low and high
white all the time

*

Nothing patching the sky: might be
the slow bite of the beginning
or something nearing the end…

always the weather,
and each expedition entering weather,
always the one event of the wind…

Bill Manhire
(Manhire, Noble, Meehan, & Griffin, 2012)

Antarctic explorers Vivian Fuchs and Sir Edmund Hillary defined whiteout as “a condition of diffuse light when no shadows are cast, due to a continuous white cloud layer appearing to merge with the white snow surface. No surface irregularities of the snow are visible, but a dark object may be clearly seen. There is no visible horizon” (1959, p. 297); such whiteout is seen in Anne Noble’s photograph Whiteout #8 (Figure 1.0). This description could also express the experience that one can have while navigating within a virtual environment or digital building model. This sense of whiteout highlights the loss of subtle cues that we all use in spatially orienting and locating ourselves, and it increases anxiety. Within a digital architectural model, moments of ‘whiteout’ are disorientating. Because of current technology, most three-dimensional digital model software relies solely on visual sense to orient oneself. The navigation tools in such software offer little in the way of feedback. Becoming disorientated or lost inside a digital model is common, and such problems range from walking into a wall to losing the whole model. In this condition of whiteout, users can become confused and frustrated, resulting in an unproductive experience. People orient themselves based on sensations received from the eyes, ears, muscles, and skin. The reduced and detached sensory offerings of digital models affect people’s development of cognitive maps. A key question then arises: How can other methods of navigation improve spatial cognition inside digital models?

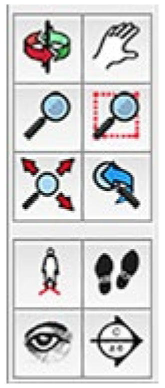


Figure 1.1
The navigation toolset from SketchUp 2014, a popular three-dimensional modelling programme. The tools are Orbit, Pan, Zoom, Zoom Window Zoom Extents, Previous, Position Camera, Walk, Look Around, and Section Plane. These are typical navigation tools for three-dimensional digital models.

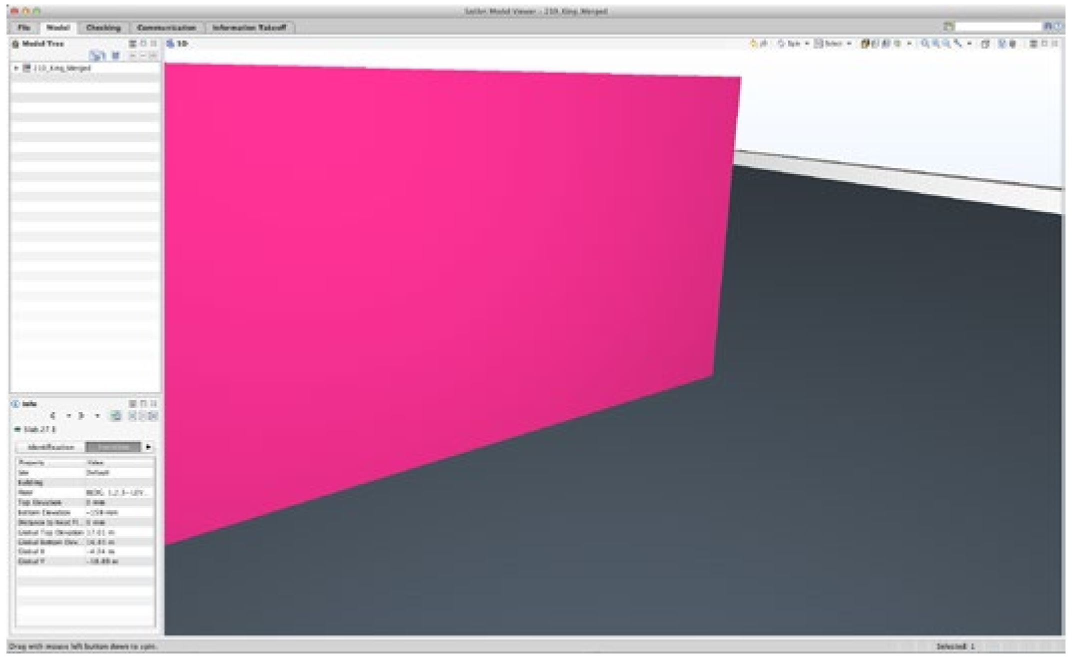


Figure 1.2
A screen capture at the moment of disorientation or whiteout inside a detailed building information model of Autodesk Research's office building at 210 King Street, Toronto, as viewed with the Solibri model viewer using the Orbit navigation tool.

Digital architectural models have become increasingly used across both architecture and construction practices. Such models were initially used for visualisation only, but now with the rapid adoption of building information modelling (BIM), the use of digital architectural models is "revolutionising the way the building partners practice and document their work" (Kensek & Noble, 2014, p. 13). The initial benefits of BIM have included a reduction in time spent identifying and rectifying errors of design and construction, and a facilitation of communication. Professor Chuck Eastman and co-workers (Eastman et al., 2011) predict that information integration will be the next step in the development of BIM. However, to support further information integration, improvements in spatial cognition need to be addressed.

Problems Navigating Digital Space

Navigation and orientation within digital models is a significant and ongoing problem for people of all skill levels (Chen & Stanney, 1999; Kopper, Tao Ni, Bowman, & Pinho, 2006), often impaired by poorly designed navigation tools (Sebok, Nystad, & Helgar, 2004) (as shown in Figure 1.1), resulting in difficulty navigating (Dodiya & Alexandrov, 2008). It is common for a person to become 'lost' within a model (Burtnyk, Khan, Fitzmaurice, Balakrishnan, & Kurtenbach, 2002) resulting in an "unproductive and unpleasurable experience, even when trying to do the most basic three-dimensional navigation operations" (Fitzmaurice, Matejka, Mordatch, Khan, & Kurtenbach, 2008, p. 7).

In avoiding moments of whiteout, "maintaining knowledge of current position and orientation is frequently a problem for people" (Darken, 1993, p. 157). One of the key problems in navigating digital space is that "typical three-dimensional software applications do not account for the scale of the environment within their navigation tools" (McCrae, Mordatch, Glueck, & Khan, 2009, p. 7), making it hard to understand the size of what is being viewed (Figure 1.2). This is true even if the model is being drawn at a 1:1 scale and viewed from a third-person perspective. As Michael Glueck and Azam Khan state:

> *Virtual three-dimensional environments are paradoxically difficult for humans to interact with, given our countless daily interactions with a variety of real world three-dimensional environments. Users can feel disoriented, confused, and even lost if they are no longer able to recognise what they are viewing, which in turn makes recovering to a familiar or understandable view difficult. (Glueck & Khan, 2011, p. 393)*

A traditional definition of navigation, as defined in The American Practical Navigator, is "the process of planning, recording, and controlling the movement of a craft or vehicle from one place to another" (Bowditch, 2002, p. 803). This is a very narrow definition of navigation that excludes consideration of a broader scope of movement. In this exegesis, I am interested in a broader sense of navigation, one that can refer to the action of determining position and direction, including pedestrian navigation. Another more helpful definition, that of Professor of Computer Science Laura Leventhal, is that “navigation is the cognitive process of acquiring knowledge about a space, strategies for moving through space, and changing one’s meta-knowledge about a space.” (Jul & Furnas, 1997).

Donner Professor of Science at Harvard University, John Huth, argues that “all navigational cultures have to deal with similar challenges: spatial orientation, the ability to estimate distances and find position from environmental clues” (Huth, 2013, p. 8). These three challenges are made even harder in digital models because of the redaction of environmental clues. Research has resulted in solutions for aiding spatial orientation and location from digital environmental clues. However, there are no clear methods to aid distance estimation.

Urban planner Kevin A. Lynch defined the term ‘wayfinding’ in 1960 (Lynch, 1960, p. 3) as “a consistent use and organization of definite sensory cues from the external environment.” In 1984, architect and environmental psychologist Romedi Passini broadened the definition to include signage, clues inherent in a building’s spatial grammar, logical planning, audible communication, tactile elements, and accessible provision for users (Passini, 1984). Wayfinding as a term has been adopted and used by multiple disciplines, including architecture, geography, design, and tourism. Passini (1996) identified wayfinding as a major design issue in the case of the built environment, and I argue that it is also the case within digital architectural models.

The aforementioned problems raised are not new, and will continue. Having been clearly identified at the 1997 Navigation in Electronic Worlds Workshop, and although definitive solutions were not reached, it was clear that “improved support for navigation is increasingly needed” (Jul & Furnas, 1997, p. 1). The original contribution that I offer here is that of a spatial information architect, using a transdisciplinary design research approach that builds on an understanding of complex space. The core of the research to which I refer has focused on two separate areas, namely, spatial cognition and navigation in the natural and built environments and with particular regard to what are commonly termed virtual environments. Even though these two areas reference each other’s work, the problems of navigating complex three-dimensional space has only recently started to be addressed. For example, Professor of Behavioural Neuroscience at University College London, Kathryn Jeffery, and her co-workers state that “the study of spatial cognition has provided considerable insight into how animals (including humans) navigate on the horizontal plane. However, the real world is three-dimensional, having a complex topography including both horizontal and vertical features, which presents additional challenges for representation and navigation” (Jeffery, Jovalekic, Verriotis, & Hayman, 2013, p. 523). In 2008, Autodesk Research published and implemented one of the most productive orientation and

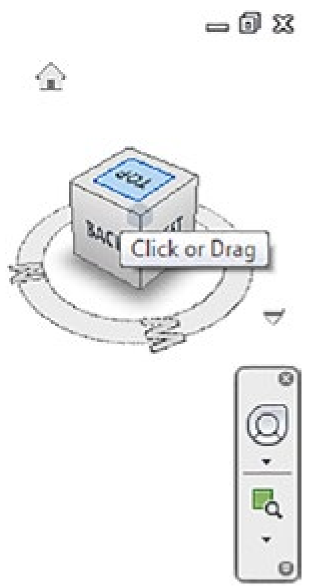


Figure 1.3
ViewCube a three-dimensional orientation indicator and controller, developed by Autodesk Research, 2008. Now Autodesk's standard orientation controller across their three-dimensional software range.

navigation tools for digital modelling and viewing, ViewCube widget (Figure 1.3), a three-dimensional Orientation Indicator and Controller (Khan, Mordatch, Fitzmaurice, Matejka, & Kurtenbach, 2008) that is now standard across the company's three-dimensional software products. The widget is an example of assisting users to orient themselves around a three-dimensional digital model. However, the widget provides only global orientation, and does not provide location or indicate the scale inside the interior of a digital architectural model.

John Huth explains the connection between navigation and spatial cognition, relating the scale and speed of movement to an understanding of space:

> *How does the mode of transportation affect our perception of space? If we walk around where we live, we're probably familiar with the details of our house, the sidewalk outside, and the trees down the block. If we walk farther away, we may recognize most houses, but we've lost some of the details; we might not realize if someone's changed his mailbox. If we drive around town, we may know the major intersections and even shortcuts to avoid traffic, but we probably won't know the names of all the side streets. If we drive (without a GPS device) to visit an aunt who lives five hundred miles away, we'll remember some of the major waypoints on the interstate, but if we haven't visited her in a while, there's a chance we might get lost after we've gotten off the freeway. (2013, p. 26)*

A number of digital environment software programmes have introduced simple spatial transitions beyond an instant teleport between locations, aiding spatial cognition. However, there are no tools that provide transitions responsive to the interior.

Architectural Documentation

The methods used for communicating architectural designs to others have continuously evolved alongside the technology of the time, from a master builder explaining and building on site to an architect drafting plans and sections on paper. Subsequently, there was the introduction of Computer-Aided Design (CAD), which replicated hand-drafting methods, and then the emergence of BIM, which has been followed by the emerging exploration of direct three-dimensional printing of building parts and buildings.

Architectural working drawings are based on conventions, with every architecture practice adjusting the appearance of projections at standard scales from site to detail, together adding up to a complete objective conception of a building (Pérez-Gómez & Pelletier, 2000). These projected representations are annotated and cross-referenced between scales and views of the dissected building. Parchment and linen and later paper were common substrates for working drawings requiring labour-intensive duplication processes. In the twentieth century, tracing paper enabled mechanical reprographic reproductions of drawings to be made for distribution. The adoption of desktop computing digitally translated these drawing practices, with CAD software providing productivity increases and new possibilities of complex geometry. BIM software has enabled the building to be represented as a complete edifice. In connection with these changes in the technology of working drawings, there has also been an increase in the number of drawings required to construct a building (Pollalis, 2006). This can be attributed to a number of conditions, including changes in architectural practice, more risk management, increases in drawing productivity, the increased complexity of buildings, and to a lesser level, changes in trade skill sets from craft to installer.

To help leverage the BIM process, the user interface of the digital model needs further development: “efficient navigation is essential for the user-acceptance of the virtual environments” (Dodiya & Alexandrov, 2008, p. 339). My research focuses on the interface of navigation and spatial cognition inside digital architectural models, with the interior of the building being key. For the scope of my research, I refer to digital models of architecture as digital architectural models, rather than to BIM, virtual environment, or virtual reality. By doing so, I focus attention on the model geometry.

Spatial Cognition

Spatial cognition is a branch of cognitive science that seeks to understand how both people and animals perceive, interpret, mentally represent, and interact with the spatial characteristics of their inhabited environments. These characteristics include the properties of size, shape, and scale, as well as the relations of distance, direction, orientation, and location (Waller & Nadel, 2012). Within the diverse field of spatial cognition, I focus on cognitive mapping—the process of acquiring, storing, and accessing environmental characteristics internally—which I explore in more detail in Chapter 2.

Aim

The aim of this research is to examine and explore methods of improving spatial cognition through aiding navigation inside three-dimensional digital architectural models. This research sets out to advance navigation of BIM models to expand people’s spatial cognition improving design, construction and building operation.

Method

The challenges of developing a compelling understanding of spatial cognition inside digital models are vast and need to span between simplicity and complexity. Because of the complexity of the spatial problem, key elements required investigation in both isolation and simplification.

Following Peter Downton's opening sentence in 'Design Research' (2003) that "Design is a way of inquiring, a way of producing knowing and knowledge; this means it is a way of researching," my exegesis is positioned as design research by project. As a spatial information architect, the projects followed architectural design research strategies in the search for improving spatial cognition inside digital models, not in the design of buildings.

I use the research method of reflective practice of project-based design investigations, drawing on Donald Schön's concept of 'reflection-in-action' (1983) to describe my intuitive understandings and advance knowledge while simultaneously aiming to solve practical problems (Schwandt, 2007, p. 3). This underlying strategy is conducted through the interrelated experimental design investigations as project works through a range of digital model interfaces, in conjunction with a review of the literature. I have grounded the projects "in a qualitative research paradigm whose purpose is to gain greater clarity and understanding of a question, problem, or issue" (Stringer, 2007, p. 19).

The project-based design work is not architecture in the sense of designing a building or part thereof; rather, it involves the exploration of architectural principles of design, spatial interfaces, and wayshowing inside digital models. Drawing on my experience of architectural practice and teaching, I produce methods to aid in navigating digital architectural models to improve spatial cognition. Proprietary software demanded an exploration of non-BIM platforms, requiring replicating a detailed building information model within a flexible platform that enabled an exploration of navigation tools. Four software titles were utilised, all with their own strengths and limitations, as discussed in the project-based design investigations.

Scope

During the research process, possible areas of focus developed, many with connections to each other. Because of the body of existing knowledge surrounding navigation, spatial cognition, and virtual environments, I approached the research through the lens of architectural design. The research focuses on aiding navigation within the interior of digital architectural models to bring about an improved spatial cognitive experience. The research is concerned with the spatial cognition in completed architectural building models; the creation or authoring of digital models is outside the scope of my research. Once a model is completed, the process of understanding the building's spatial configuration is time consuming, often resulting in misunderstandings.

Of the existing research areas that fall with this field, the present research does not include methods and issues surrounding digital model authoring, automated building code checking, and the travelling salesman problem. There has been extensive research in the area of automated building code compliance (Dimyadi & Amor, 2013), including fire egress pathways, and although important this is beyond the scope of my research. The travelling salesman problem, determining the shortest distance between a collection of addresses, is "one of the most intensely investigated problems in computational mathematics" (Applegate, Bixby, Chvátal, & Cook, 2011, p. 1). Although that problem and its solutions may inform future research, it too lies beyond the scope of my exegesis. It is important to acknowledge the differences that people have: we all process spatial knowledge differently depending on our background, gender (Suma, Finkelstein, Clark, Goolkasian, & Hodges, 2010a), and abilities (Kilduff & Miner, 2010). These differences were considered during the present research, but are not central to its scope.

Structure (map)

To facilitate navigation, the exegesis is split (charted) into five chapters: this introduction, a background chapter consisting of three sections, a project chapter consisting of three sections, a discussion chapter, and a concluding chapter.

In Chapter 2 I set up the background condition to the project works by shaping the context, setting the research methods, and surveying related work.

Section 2.1 provides context by defining spatial cognition, cognitive maps, wayfinding, navigation, pathfinding, and wayshowing, which set the foundation for providing a framework to improve spatial cognition within digital architectural models. I outline the technological transformation of architectural communication from a collection of varying scribed lines on a flat artefact to being able to construction complete digital replications across multiple dimensions.

Section 2.2 outlines the research methods that I use in the exegesis to map project-based design investigations. I position my research as a reflective practice of design projects that are simultaneously method, instrument, and result, defining and informing my research and acting to triangulate findings.

Section 2.3 surveys and critically assesses related work in relation to my own. I introduce and discuss key knowledge to clearly articulate the path that the research develops in contributing to the advancement of knowledge.

Chapter 3 represents the project-based design investigations that were constructed to explore and test methods of navigation and spatial cognition inside digital architectural models.

Section 3.1 outlines preliminary projects and discribes their outcomes, which are the translation of the two-dimensional drawing conventions of section, exploded axonometric, and information markers within an interactive digital model. This clearly expresses the limitation of translating two-dimensional drawing conventions to three dimensions. The main conclusion of this project is the clear need to improve the interface of building information models. The section outlines failed projects and describes their failings, which were used to inform the projects in Sections 3.2 and 3.3.

Section 3.2 investigates other navigation tools that were not common within BIM software. The section describes four projects that develop and critique a range of navigation and wayshowing methods within digital models. The projects position spatial cognition via wayshowing, enabling navigation to become an important site of contribution, a site that has seen considerable advancement in accessible authoring interfaces of artificial intelligent pathfinding tools in computer game engines.

Section 3.3 investigates ways of adding interiority to spatial transition to aid the estimation of distance and scale. The section outlines four projects that transition views within digital architectural models from artificial intelligence (AI) pathfinding to tools that intuitively guide people in comprehending the size of space and distance travelled.

Chapter 4 orients these design projects together, locating limitations and discusses a framework of navigation tools, wayshowing, and pathshowing methods that can improve spatial cognition. I argue the need for improving spatial cognition by understanding distance, detail, data, and design while reviewing digital architectural models. These areas have implications for how architecture is understood in both education and practice.

Chapter 5 concludes the thesis, acknowledging the range of conditions required to improve spatial cognition, specifically those covered in chapter 4, locating my contribution to the field of architectural design.

Figure 2.0
Antarctica: The Grain of White #24, Anne Noble, (2009). Inside an unknown space, disoriented.

2 Background

Finding a path

This chapter contains three major sections:
2.1 Context
2.2 Research Method
2.3 Related Work

The train squeals to a stop and the door slides open, this is the station at which I need to exit the train. Minding the gap, I am forced out with everyone else leaving the train. Which way do I need to go to get to the correct exit? There are too many options, I cannot see all the signage. I pick the nearest exit. Following the signs, turning left, right, going up, then down and another left; into a space so loud with people rushing past I cannot think. Finally, I emerge from the artificially lit rabbit warren onto a bustling street. Which way do I need to go? This experience of being ‘dropped’ in the middle of a dense unknown space is a disorienting one, resembling the conditions of an urban whiteout, the feeling of disorientation, that of being in a whiteout (Figure 2.0). Similar feelings are often encountered upon exploring three-dimensional digital models.

I reveal in this exegesis the ongoing need for improved navigation tools in digital architectural models. My motivation for the research is to improve spatial cognition inside digital models. I introduce the concept of cognitive maps, a type of mental representation that people use to acquire, code, store, and recall spatial environments to help with wayfinding and navigation. I break down navigation to three key elements: spatial orientation, estimating distances, and locating position (Huth, 2013) to categorise the literature of navigation in virtual environments. This reveals the focus on spatial orientation and locating position, with a clear problem of enabling accurate distance estimation in digital environments. This chapter comprises three sections. The first section (2.1) provides context to this research, defining key terms and tracking the development of architectural documentation from verbal instructions to information-dense digital modelling processes of collaboration; this makes evident the need to improve spatial cognition in digital architectural models. Section 2.2 outlines the research method of design research by project, including the research tools used and the criteria for evaluation. Section 2.3 examines and critically assesses others’ work in relation to my own, including work on navigation tools, spatial orientation, location tools, distance estimation, and digital architectural models.

Figure 2.1
Williams Field #9, Anne Noble (2002)

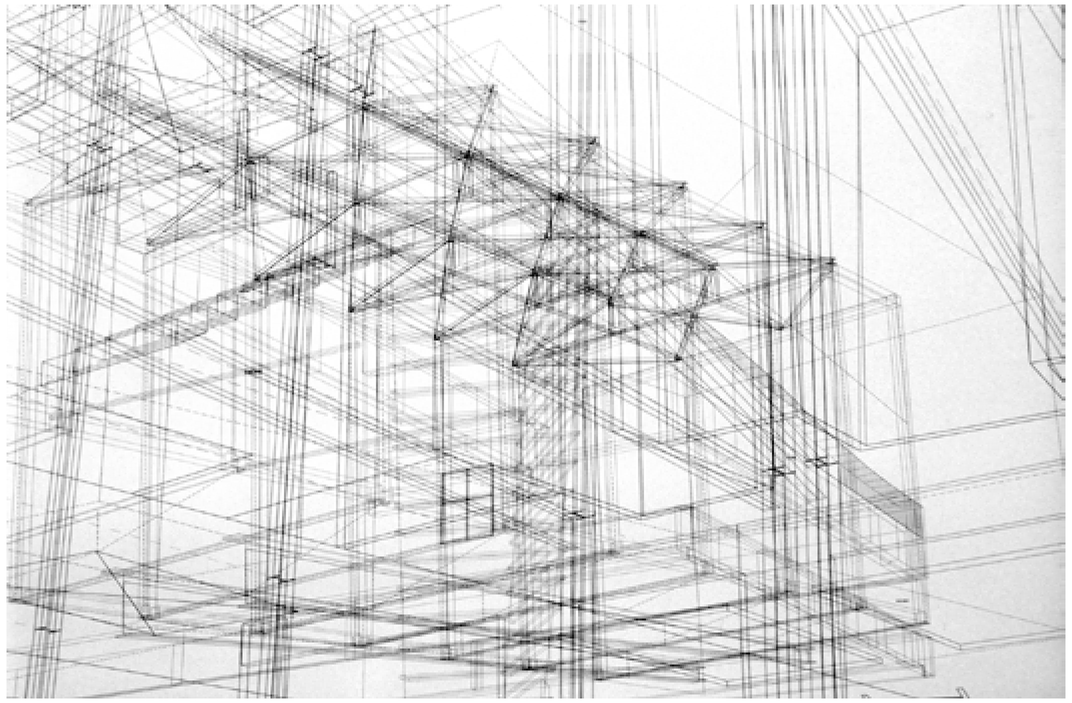


Figure 2.1.1
Early digital architectural model exploration, modelled from only lines, not solid objects.

2.1 Context

Within this section, I set out the context of this research by providing my motivation for undertaking this journey of exploration. I then define the key concepts of spatial cognition that enable cognitive mapping, wayfinding, and navigation, leading on to wayshowing. Following this, I outline a brief history of architectural documentation, starting from a mental image that was described orally through to multidimensional digital architectural models, including how these models are viewed, addressing the moments of feeling lost (Figure 2.1).

Motivation

The first computer drawing I constructed as an architecture student was in three dimensions using AutoCAD in 1995. I began by drawing lines in three-dimensional digital space, thinking that a model would form, only to find that I had constructed a stick figure that was completely transparent and hard to visualise (Figure 2.1.1). I then had to redraw the entire model as solid objects. During this first exploration in CAD, there were numerous times when I would 'lose' the model or be looking at it incorrectly. Since that first model, I have continued to model in three dimensions from study in architecture to practice, and while teaching students how to draw digitally I have observed people becoming lost. In the intervening period, architectural software has developed considerably, enabling highly detailed, nearly complete replications of real buildings to be created. Although the navigation tools have developed, the problem of becoming 'lost' remains. The motivation for this research is to explore methods of improving spatial cognition inside digital architectural models.

Spatial Cognition

The way in which people understand the environment they are in, and how we know where to walk, is with a cognitive map or internal spatial representation of environmental information. The term 'cognitive map' was introduced by psychologist Edward Tolman (1948). Cognitive mapping is considered to be a branch of spatial cognition (Golledge & Stimson, 1997). Spatial cognition is concerned with the way we acquire, organise, utilise, and revise knowledge about spatial environments. The Handbook of Spatial Cognition (Waller & Nadel, 2012) defines spatial cognition as a branch of cognitive science that seeks to understand how people acquire, interpret, use, and communicate knowledge about their environment in order to determine relationships of distance, direction, orientation, and location.

Within the scope of my research, understanding cognitive mapping is critical. The way in which people gain spatial cognition while exploring unfamiliar environments is by building a cognitive map. The process of cognitive mapping has been described by Roger Downs and David Stea as "a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment" (Stea & Downs, 1973, p. 9). Barbara Tversky explains that:

> *People acquire disparate pieces of knowledge about environments, knowledge that they use when asked to remember an environment, describe a route, sketch a map, or make a judgment about location, direction, or distance. The separate pieces include recollections of journeys, memories of maps, recall of verbal (aural or written) directions and facts, and more. (Tversky, 1993, p. 14)*

Cognitive maps are individual, sorting salient details, combining both sensory and motor information in the hippocampus. In helping to express what a cognitive map is, Robert Kitchin (1994, p. 5) produced a collection of expressions used as an alternative to or to imply 'cognitive map'. They include:

abstract maps (Hernandez, 1991);
cognitive configurations (Golledge, 1977);
cognitive images (Lloyd, 1982);
cognitive maps (Tolman, 1948);
cognitive representations (Stea & Downs & Stea, 1973);
cognitive schemata (Lee, 1968);
cognitive space (Montello, 1989);
cognitive systems (Canter, 1977);
conceptual representations (Stea, 1969);
configurational or layout representations (Golledge, Briggs, & Demko, 1969; Kirasic, 1991);
environmental images (Lynch, 1960);
imaginary maps (Trowbridge, 1913);
mental images (Pocock, 1973);
mental maps (Gould, 1966; Gould & White, 1974);
mental representations (Gale, 1982);
orienting schemata (Neisser, 1976);
place schemata (Axia, Peron, & Baroni, 1991);
spatial representation (Allen, Siegel, & Rosinski, 1978);
spatial schemata (Lee, 1968);
survey representation (Stea & Downs & Stea, 1973);
topological representations (Shemyakin, 1962);
topological schemata (Griffin, 1948); and
world graphs and cognitive atlases (Lieblich & Arbib, 1982).

I add to this list the following:
cognitive collage (Tversky, 1993); and
survey knowledge (Golledge, 1999b).

Cognitive maps are approximations of the environments in which people travel rather than absolute representations. They can contain multiple scales of information constructed from all of our senses, and represent

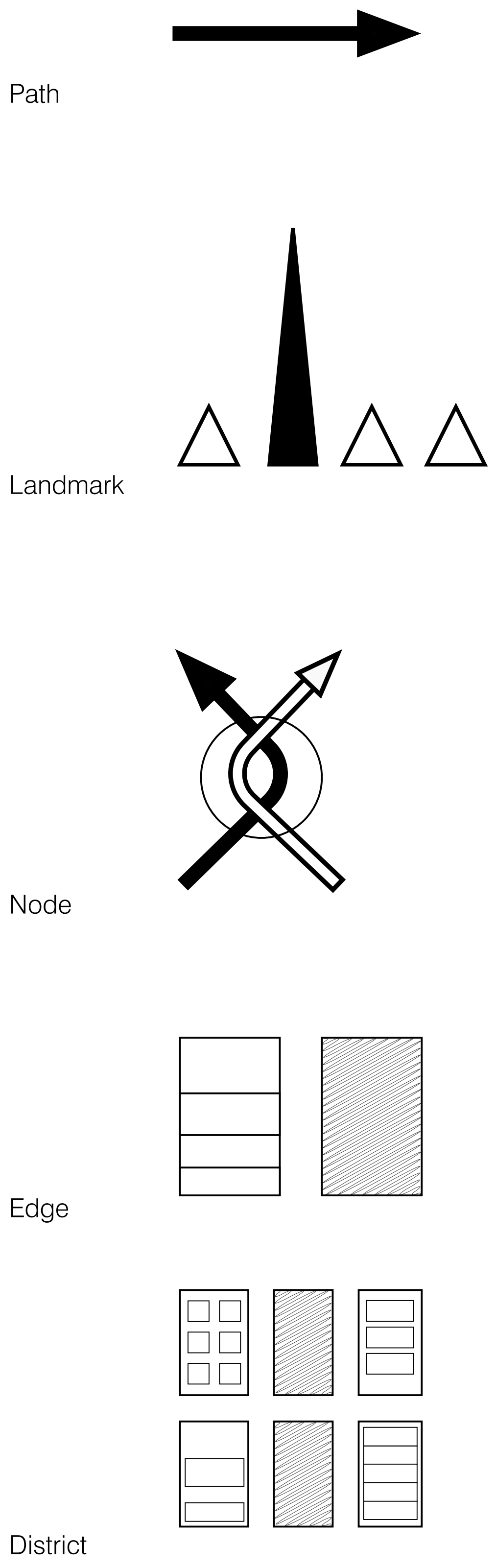


Figure 2.1.2
Kevin Lynch's (1960, pp. 47–48) five elements; paths, landmarks, nodes, edges, and districts that make up a mental image of a city.

the spatial relationships of elements that inform an environment (Nadel, 2012). Professor of Geography at the University of California, Reginald Golledge, and Emeritus Professor of Geographical Sciences and Planning at University of Queensland, Robert Stimson, argue that "cognitive maps are not to be thought of as isolated entities but as being contextual, dynamic, and providing the interface mechanism between sensed information and behavior" (1997, p. 235). Visual may be the prominent type of information used when creating cognitive maps, but it is not clear how much influence the other senses have on their construction (Sholl, 1996, p. 157). People construct and read cognitive maps differently from each other. "An individual's experience of an environment determines which locations are experienced and in which sequence" (Ghiselli-Crippa, Hirtle, & Munro, 1996, p. 89). People vary in how they understand their environments, from being completely lost to knowing their orientation and in which direction they need to travel. In the influential book 'The Image of the City', American urban planner Kevin Lynch identifies five elements that make up the mental image of a city. (Lynch, 1960, p. 47) (Figure 2.1.2):

- Paths (along which movement flows)
- Landmarks
- Nodes
- Edges (which differentiate one part of the urban fabric from others)
- Districts

Architect and environmental psychologist Romedi Passini (1984) extends Lynch's notion of the environmental image in the city to cognitive mapping in architecture and beyond, including graphics and signage.

All cognitive maps contain errors and differences. "Errors incurred during the encoding phase of knowledge acquisition can produce distortions in the material stored" (Golledge, 1999b, p. 23). Kevin Lynch (1960) notes that errors in cognitive maps are frequently metrical and seldom topological. In order not to simplify people's cognitive maps or fixate on errors, I decided not to use sketch maps as a measure of spatial cognition as done by Billinghurst & Weghorst (1995) and Suma et al. (2010b) for testing virtual environments. A sketch can provide only a fraction of spatial knowledge. People's backgrounds and experiences influence spatial cognition during a specific task inside digital architectural models. However, spatial visualisation ability and gender difference are outside the scope of my research.

Virtual environments have been used in numerous previous studies to test spatial cognition either in comparison to the physical world or only within the digital environment, but of these approaches are instrumental to the present research study, while the digital model is the central focus, as a representation of an existing or proposed real building.

Wayfinding

> *Due to its ubiquity in everyday life, wayfinding appears on the surface to be a simply characterized and understood process; however, this very ubiquity and the resulting need to refine and optimize wayfinding has led to a great number of studies that have revealed that it is in fact a deeply complex exercise (Farr, Kleinschmidt, Yarlagadda, & Mengersen, 2012, p. 715)*

Reginald Golledge defines wayfinding as the "process of determining and following a path or route between an origin and a destination. It is a purposive, directed, and motivated activity" (Golledge, 1999b, p. 6). This process is intrinsically connected to the cognitive map, a product of immediate sensation and past experience (Lynch, 1960).

Wayfinding is a temporal problem-solving process of finding a route from one location to another (Mollerup, 2013, p. 19). Wayfinding is intimately tied to motion "in a complex negotiation that is navigation. An essential part of wayfinding is the development and use of a cognitive map" (Darken & Peterson, 2001, p. 493). A perceptual flow is constantly referenced to update the process of arriving at a new location. The term 'wayfinding' has become misused to refer to signage and environmental information design. In his book 'Wayshowing', Professor Per Mollerup (Mollerup, 2005) defines wayshowing to distinguish it from wayfinding. I explore wayshowing in more detail further below in this chapter. According to Per Mollerup's definition of wayshowing, the book 'The Wayfinding Handbook' by David Gibson (2009) would be more accurately named 'The Wayshowing Handbook'.

The wayfinding process (Mollerup, 2013, p. 22) involves the following:

Planning
- Decision to move
- Seeking information – search
- Checking internal information
- Checking external information
- Computing alternative routes
- Selecting eligible routes
- Choosing criteria
- Evaluating eligible routes
- Choosing route – Decision

  > **Mental solution** = Plan

Execution
- Move / Search / Decide / Move

  > **Physical solution** = Journey completed

The nine wayfinding strategies according to Mollerup (2013, p. 26) are:

1. **Track following**
   Following signs, lines, or other tracks
2. **Route following**
   Following a plan
3. **Educated seeking**
   Using prior knowledge
4. **Inference**
   Concluding from sequential designations
5. **Screening**
   Systematic searching
6. **Aiming**
   Visual targeting
7. **Map reading**
   Using portable and you-are-here maps
8. **Compassing**
   Using compass directions
9. **Social navigation**
   Learning from others

The experience of even momentary disorientation and a lack of recognition in one's environment is the unsettling experience of being 'lost'. This state occurs when the wayfinding process fails. To understand how to reduce moments of 'lostness', it is necessary to know about human wayfinding and the cognitive and environmental factors that influence it (Golledge, 1999a). Wayfinding includes all of the methods with which people and animals orient themselves in space and progress via navigation to places. Moving is critical to build spatial cognition of any space. The term wayfinding was first introduced by Kevin Lynch in his book 'The Image of the City' (1960) to describe the link between wayfinding and cognitive maps or, as he terms it, environmental image. In their book 'Image and Environment', (Downs & Stea, 1973), Roger Downs and David Stea widened the definition to include perceptual, cognitive, and decision-making processes necessary to find one's way. As with cognitive maps, Romedi Passini extended wayfinding from the exterior to include architecture and the interior (Passini, 1984). He subsequently argued that wayfinding is a distinct design issue (Passini, 1996).

Professor Emeritus of Architecture at Berkeley, Yehuda Kalay, states that "research shows that difficulty in findings one's way in a complex building is costly in terms of time, money, public safety, and stress that results from being lost" (2004, p. 208). Although referring to physical buildings, Yehuda Kalay's statement also holds true within digital architectural models. With an increasing user base, people other than just the model authors are using the models, for example, in BIM.

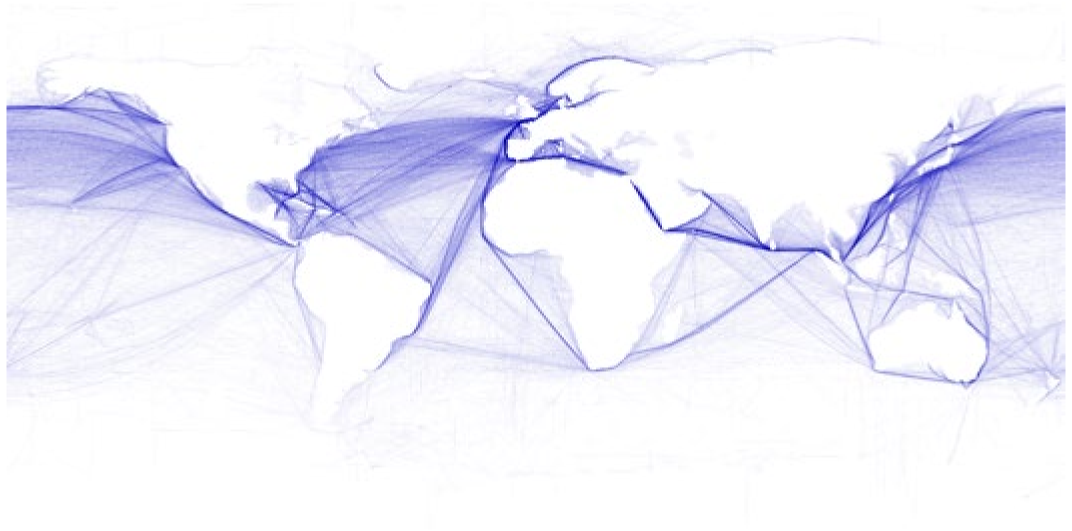


Figure 2.1.3
Commercial global shipping density, highlighting ships' navigated routes between ports.

Cognitive scientists Jan Wiener and co-workers (2009) proposed a taxonomy of wayfinding tasks classified by the existence of an external aid, a specific destination, and the availability of different levels of knowledge. Those authors divided wayfinding into unaided (no assistance) and aided (signage, maps, navigation), and then divided unaided wayfinding into either directed wayfinding (specific destination) or undirected wayfinding (no specific goal). From this point of view, the destination, route, and survey knowledge all have an impact on searching and following. The primary task for which digital architectural models are used is general spatial cognition, with a secondary task being comprehension of detail.

Navigation

Navigation is the interplay of spatial cognition, cognitive maps, and wayfinding with motion. Now people move through space. "Each of us is a navigator; we are constantly finding our way in our environment" (Huth, 2013, p. 2). Be it a simple change of rooms or a cross-country road trip, we are always navigating. The epitome of navigation, 'The American Practical Navigator' (bicentennial edition), defines navigation as:

> *The process of planning, recording, and controlling the movement of a craft or vehicle from one place to another. The word navigate is from the Latin navigatus, the past participle of the verb navigere, which is derived from the words navis, meaning "ship," and agere meaning "to move" or "to direct." Navigation of watercraft is called marine navigation to distinguish it from navigation of aircraft, called air navigation. Navigation of a vessel on the surface is sometimes called surface navigation to distinguish it from navigation of a submarine. Navigation of vehicles across land or ice is called land navigation. The expression polar navigation refers to navigation in the regions near the geographical poles of the earth, where special techniques are employed. (Bowditch, 2002, p. 803)*

This definition has been expanded over the two hundred years since the book was first published beyond just a ship or vehicle to include the process that people undertake during travel in both the physical and digital environments and across multiple dimensions. We have developed many techniques and methods to assist navigation, including close readings of the weather, stars, landscape, seascape, markings and signage, and using tools such as the sextant, compass, and global positioning system (GPS) devices. Figure 2.1.3 traces major global shipping paths as an example of this. Navigation is the task of both wayfinding towards a distant spatial location and locomotion in response to sensory information. "There is no one 'proper' way to navigate. Many individuals and cultures emphasized different skills….A good navigator will call on multiple sources of information to complete a successful journey" (Huth, 2013, p. 8).

However, in BIM models, the sources of information are drastically limited; there is no wind blowing in your face, no use of sound to describe spaces (unlike in computer games), no desired paths to follow, and rendered geometry is typically the only information available. Within desktop virtual environments, navigation is controlled by abstract input devices (mouse and keyboard), and information is affected by a limited field of view that provides different visual and kinaesthetic feedback compared with the real world. "These differences may mean that spatial knowledge formed in a virtual environment is different from that formed in the real world or is formed at a different rate" (Ruddle, Payne, & Jones, 1997, p. 144). This quote is important to reconsider nearly 20 years later, as people form cognitive maps differently in the real world compared with in the digital world (Aghajan et al. 2015, and Taube, Valerio, & Yoder, 2013). Aiding navigation will help align the differences. This can be seen with the move from road maps to GPS wayshowing devices. In the case of driving, focus is taken away from navigating to driving.

Orientation and wayfinding in digital models can be categorised into two main groups: object-based (Khan et al., 2008; Ziemek, Creem-Regehr, Thompson, & Whitaker, 2012) and fully immersive virtual environments (Bowman, Koller, & Hodges, 1997; Burigat & Chittaro, 2007; Darken & Peterson, 2001). My research is focused on a screen interface for object-based digital buildings. I draw on research conducted in fully immersive and desktop virtual reality environments because of the parallel conditions of real-time three-dimensional computer graphics.

John Huth's quote "All navigational cultures have to deal with similar challenges: spatial orientation, the ability to estimate distances and find position from environmental clues" (2013, p. 8) holds true for any environment. The culture of digital architectural model navigation requires these three key elements of navigation: spatial orientation, estimating distances, and locating position. The research literature of navigation in virtual environments has developed strategies for aiding orientation (Darken & Peterson, 2001; Khan et al., 2008) and for locating one's position (Burigat & Chittaro, 2007; Suomela & Lehikoinen, 2004). Research regarding estimating distances is not as developed. Distance perception within virtual environments often results in significant underestimation of both egocentric and exocentric estimations (Mohler, Creem-Regehr, & Thompson, 2006; Mohler, Creem-Regehr, Thompson, & Bülthoff, 2010; Thompson et al., 2006). However, this may not be true for high-fidelity, low-latency, fully immersive virtual environments viewed with a head-mounted display (Interrante, Ries, & Anderson, 2006). Depth perception influences a perception of distance that is restricted on a flat computer screen. BIM models have been used to support indoor navigation back into the physical world for emergencies or checking fire codes (Isikdag, Zlatanova, & Underwood, 2013; Rueppel & Stubebbe, 2008).

No matter people's backgrounds, they all have to navigate around and within buildings, and architects and builders also have to navigate through sets of construction drawings. Drawing sets have refined and developed conventions to enable travel over and through the pages of drawings. However, these conventions do not always translate into digital documentation methods. I discuss architectural documentation conventions further below in this chapter.

Wayshowing

The 2005 book 'Wayshowing' by Per Mollerup coined the term 'wayshowing' (Mollerup, 2005). The term refers to the professional activity of planning and implementing orientation systems in buildings and outdoor areas. Before the book 'Wayshowing' was published, this professional activity was incorrectly described as 'wayfinding'. People have always practiced wayshowing by leaving clues, marks, or a cairn. Wayshowing and wayfinding relate to each other like cooking and eating. Wayshowing proceeds and enables wayfinding.

Per Mollerup states that "The term wayfinding has its own uses. Wayfinding is what we do when finding our way around unknown quarters. Good wayshowing is user-led, built on how we practice wayfinding" (Mollerup, 2013, p. 6). Mollerup lists key areas in which wayshowing can improve the wayfinding experience, namely, a self-explanatory environment, landmarks, toponomy (giving names to places), signs, maps, help desks, and previsit information. Wayshowing makes destinations recognisable by variety, hierarchy, relative position, and signs of identification. My research is not about the design of buildings to support wayshowing, even though it is important for architects to consider, although in certain cases a holistic approach to wayshowing that informs the architecture will improve navigation within BIM models. My research recognises Per Mollerup's elements of wayshowing by incorporating appropriate thinking to improve spatial cognition within digital architectural models.

Pathfinding

Pathfinding is the computation of the shortest navigable distance between two locations, often considered within the field of artificial intelligence. Artificial intelligence, a field of computer science, emerged between 1955 and 1958, and strove to build enhanced intelligence into computer systems (Nilsson, 2010). A version of the heuristic search algorithm A* (pronounced 'A star'), first presented in 1968 by Peter Hart, Nils Nilsson, and Bertram Raphael (Hart, Nilsson, & Raphael, 1968), is still one of the most commonly used base pathfinding algorithms. Many virtual environments utilise computer-controlled autonomous agents that are able to responsively navigate around the environment. Pathfinding strategies are typically the core of any AI computer-gaming movement system developed to realistically control agent movement from one location to another in a game world (Graham, McCabe, & Sheridan,

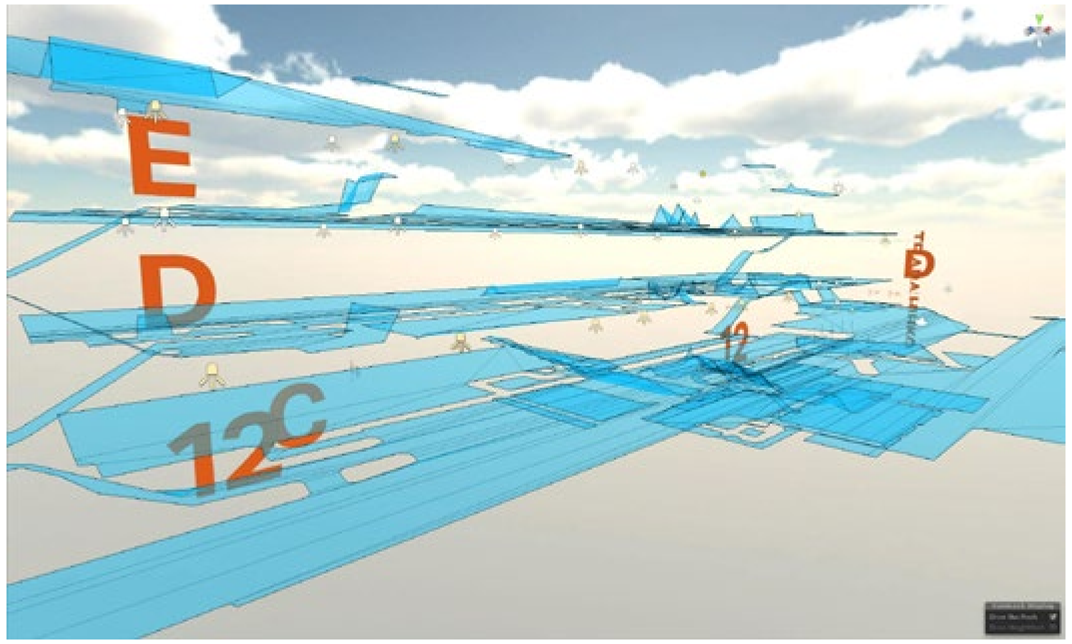


Figure 2.1.4
Navigation mesh for controlling automated pathfinding, automatically generated inside a building model, describing the walkable areas of a five-storey building.

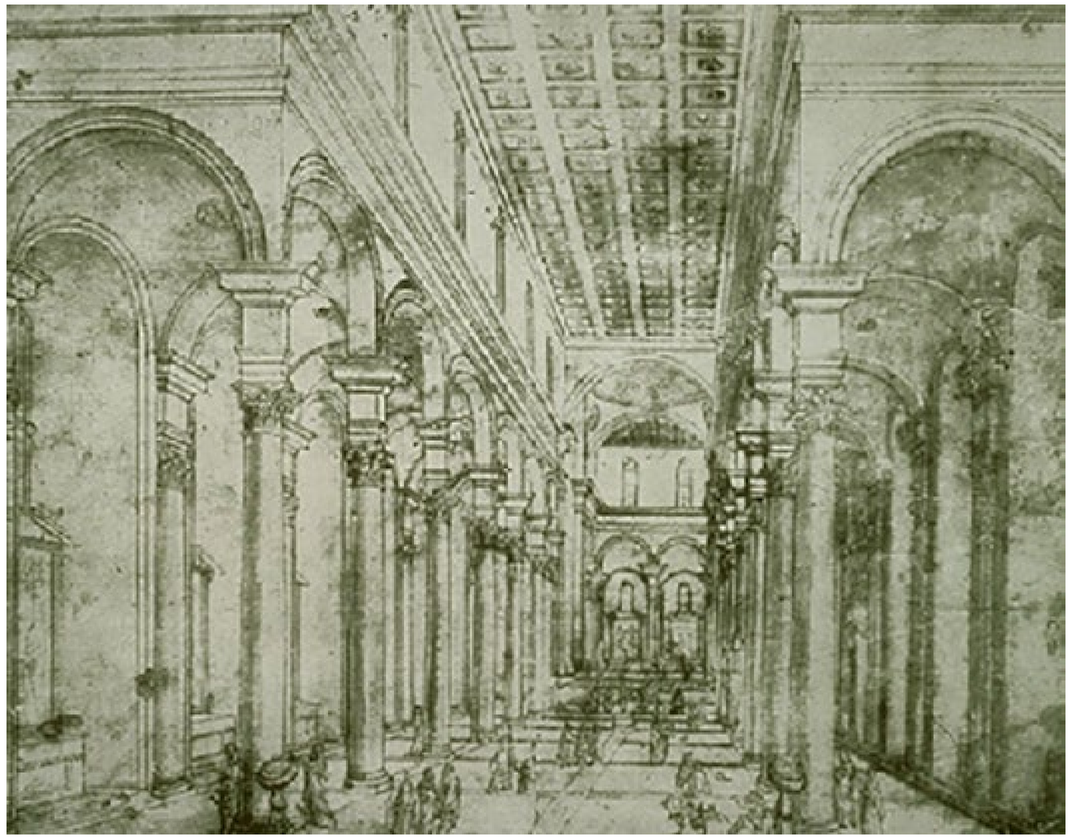


Figure 2.1.5
Filippo Brunelleschi (c. 1428). Early perspective drawing of the Church of Santo Spirito in Florence.

2003). There are various techniques that can automate the navigation of an agent or viewer to a new location. These techniques include a direct path that ignores spatial conditions (Pointer project) and spatially aware search algorithms that solve the shortest navigable path (projects Pathfinder, Space Trace, Show Me, and Te Ara Hihiko). This research is not about the algorithms used in pathfinding, nor is it about creating a new approach; rather, it utilises existing plugins and proprietary navigation systems within the software platforms investigated. These systems are based on Dijkstra's algorithm (a graph-based pathfinding algorithm) or a variant A* algorithm that improves on Dijkstra's algorithm for real-time solutions. These algorithms have also been used in the design of pathways, for virtual environments (Nieuwenhuisen, Kamphuis, & Overmars, 2007), and for physical buildings including fire-code checking (Dimyadi & Amor, 2013; Lee, 2010). Fire-code checking, which involves testing that exit paths meet local building code regulations, is beyond the scope of the present research study.

A navigation mesh is a collection of convex polygons that is created or automatically generated across a model, describing walkable areas of the environment (Board & Ducker, 2002) (Figure 2.1.4). Each of the polygons can be used as nodes in the pathfinding algorithm (Graham et al., 2003). The higher the resolution, the higher the quality of the pathfinding but also the higher the processing time, and therefore a balance needs to be found for optimum performance. Once the path has been created, a person is guided to follow the path using one of several methods: a line is drawn that can be used to guide the viewer, the person automatically traverses the path, or an agent follows the path to the new location.

Architectural Documentation

Architectural documentation has evolved alongside communication technology. Documentation has evolved from a master builder providing verbal instructions, to the use of computer drawings/models, and now to three-dimensional printing of building parts and even whole buildings.

The history of architectural documentation constitutes only a fraction of the history of architecture. Originally, only remarkable buildings were considered 'designed' using drawings and models. Full-scale drawings were drawn directly on site. Architectural historian James Ackerman writes that "We have to assume that architects and master masons were able to design in their heads and that they explained their ideas verbally and through models and templates" (2001, p. 31). It was not until the invention of perspective drawing by Filippo Brunelleschi in the early fifteenth century (Figure 2.1.5), coupled with a greater availability of paper, that architects developed ideas via drawing at scale, due to the expense of stone tablets and parchment (Riley, 2002). Enabling architects to accurately plan and express a proposed building

Figure 2.1.6
In a frame from the Lincoln Laboratory (1964) documentary, Timothy Johnson draws with Sketchpad's light-pen.

allowed architectural elements and principles to be refined. With paintings in perspective moving to orthographic projections, the major achievement of Renaissance architects was establishing the convention of orthogonal drawing. Architectural drawings progressively grew in importance during the eighteenth century: the "period of the unique copy" (Hassler & Stockhammer, 2014, p. 285). A plan and front elevation with written specifications describing the structure and materials was considered sufficient to build from (Price, 2010). Architectural scale drawings attempt to mediate architectural concept and provide construction intent by abstract representations (Hassler & Stockhammer, 2014) that invite "imaginative inhabitation of the drawing" (Emmons, 2006, p. 233), often a problem given that "three-dimensional software applications do not account for the scale of the environment within their navigation tools" (McCrae et al., 2009, p. 7). The twentieth century saw buildings of greater complexity, requiring more extensive and detailed drawings. With the possibilities of mechanical reproductions of drawings, reprographics changed the way in which design intent was transferred. "The number of plan copies seems to have increased significantly with the introduction of the blueprint process" (Hassler & Stockhammer, 2014, p. 287).

The development of the Sketchpad system at MIT by Ivan Sutherland in (1963) was the invention of the modern concept of CAD (Figure 2.1.6). Then, in 1968, Ivan Sutherland and his student Bob Sproull produced the first virtual reality and head-mounted display system (Sutherland, 1968). Computer systems began to appear in architectural practices in the early 1970s (Kalay, 2004). Early CAD platforms required large and expensive computers; it was the introduction of the graphic-oriented Macintosh in 1984 that made computer-aided drafting feasible. Digital drafting was the mainstay of CAD software, and although three-dimensional software was available, it was used for visualisation, and there was no automated method for producing architectural working drawings directly from the model. CAD replicated the manual working drawing processes: it took two lines drawn next to each other to represent a wall, and the software only knew them as vectors on a layer named 'A-WALL-FULL' (The American Institute of Architects, 2005).

Problems and deficiencies with project documentation are well documented (Eastman et al., 2011; Gallo, Lucas, McLennan, & Parminter, 2002; Teicholz, Goodrum, & Haas, 2001; Tilley, 1998; Tilley, 2005; Tilley, Wyatt, & Mohamed, 1997). Architectural practice has evolved and continues to develop: the relationship with builders is changing, the way architects draw is changing, and the way architects design is changing. Architects are producing hundreds of drawings and pages of specifications, more than they have ever before (Pollalis, 2006). This can be attributed to the increase in productivity of producing drawings, the increase in building complexity, and the increase in liability:

> *Drawings are fundamentally paper-based in format. Drawing symbols and formatting conventions have evolved primarily because paper is a two-dimensional medium; orthographic projections were essential for measuring distances on paper. If and when digital displays become sufficiently cheap and flexible to suit the conditions of work onsite, paper printouts of drawings will likely disappear. Once formal drawings are no longer printed, there will be no clear reason to maintain their formatting conventions. In the face of the superior medium of three-dimensional building information models, they may finally disappear altogether, giving way to printouts that reflect special projections, such as exploded isometrics, that can be used to guide work more effectively. In the design domain, visualisation formats will replace drawing types, with different formats developed for each of the parties involved: owners, consultants, bankers and investors, and potential occupants. These formats may include standard walkthrough views with audio and possibly tactile feedback added to the visual content. User-controlled walkthroughs will support further interrogation of the model. For example, a client may want spatial data or a developer may want to query rental rates. Integration of these services into the fee structure will add value to architectural services. (Eastman et al., 2011, p. 384)*

Architectural models are an important tool in the design process as well as in the communication of spatial intent. The architectural industry is moving from documents to a data-driven approach of design, delivery, and operations (Eastman et al., 2011). The way data are visualised, accessed, shared, and comprehended is going to define the transition from a document-centric workflow to a data-centric workflow. BIM has started this transformation.

Digital Architectural Models

In this exegesis, I refer to the term ‘digital architectural model’ to define the model created by architects, to allow attention to be placed on spatial cognition and on the navigation of the model geometry and building data. I use this term to acknowledge the specificity of the area of study and to differentiate between virtual reality, virtual environments, computer games, and BIM.

Historically, virtual reality and virtual environments have been the terms used to define a computer-simulated environment and interface that can simulate presence within a spatial world from a first-person perspective under the real-time control of the user. Virtual reality often includes the use of head-mounted displays or Cave automatic virtual environments (CAVEs) (truly immersive virtual reality environments, with multiple projectors directed onto three to six walls of a room-sized cube). Virtual environments can now be experienced on both desktop and mobile computers. User-control is received from a keyboard and mouse, touch, motion, or other objects with sensors (gloves, for example).

One of the largest users of digital architectural models other than the architectural industry is computer gaming. It is common for three-dimensional games to include architectural models within the game play. Computer games are pushing the research and development of graphic and realistic digital worlds. Games often use wayshowing mechanisms that help direct players to stay on the correct path or to find a specific location, but only rarely do they aid in distance estimation beyond recognisable detail, which can still be easily misunderstood. A notable game is Minecraft, which the creator of the independent sandbox game, Markus “Notch” Persson, revealed by Twitter in February 2014 had reached 100 million registered users (Persson, 2014). This milestone is important for two major reasons: the first is that substantial numbers of people are now familiar with navigating inside digital models in perspective, and the second is that children as young as five are creating digital architectural models within the game.

To enable digital models to be explored beyond the conventions of commercially available BIM software, computer game engines have been investigated as possible test sites (Andreoli, De Chiara, Erra, & Scarano, 2005), including Source game engine, Esperient Creator, Unity, and CryEngine. These computer game engines too had many limitations, but their limitations differed from those of BIM software; however, such engines allowed explorations to be made of both productive spatial cognition and navigation. A game engine is a software framework that enables video games to be designed. The software may include a rendering engine to display model geometry, a physics engine for collision response, and artificial intelligence for pathfinding, with each game engine offering its own response to these features. Game engines have been used to enhance architectural documentation and communication (Hoon & Kehoe, 2003).

In the exegesis, I use BIM for giving context to the research and to the area on which the research is focused. I use the term ‘BIM model’ to describe the digital model at the centre of the BIM process, and the information-rich digital visual manifestation of the architectural model, rather than the supporting processes that BIM offers.

Building information modelling or BIM is a process involving the creation and management of digital representations of information related to building, from design, through construction to operation. Although BIM is not central to my research, it is important to define and explain its relationship to my research. BIM is responsible for architecture’s direction for architectural documentation. Architects will continue to create increasingly information-rich digital models that are accessible to more people. BIM is becoming

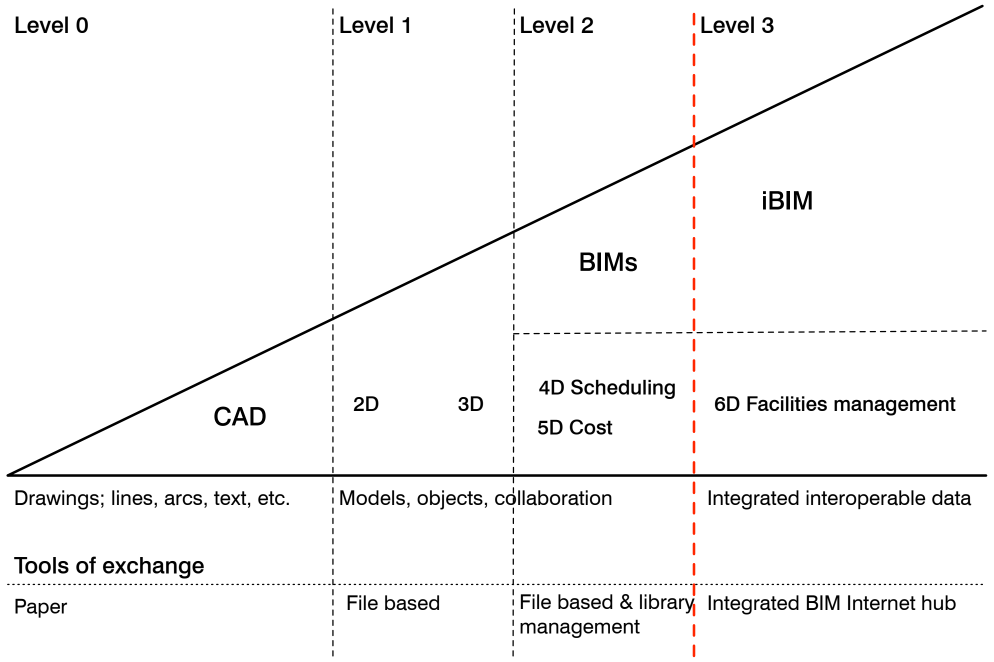


Figure 2.1.7
The progressing maturity of building information modelling with the tools of exchange at each level.

the standard process for delivering architectural and infrastructural projects. The Construction Industry Council in the United Kingdom defines BIM as

> *an innovative and collaborative way of working that is underpinned by digital technologies which support more efficient methods of designing, creating and maintaining the built environment. In essence BIM embeds key product and asset data within multidimensional computer models that can be used for effective management of information throughout the project lifecycle––from earliest inception through occupation. It has been described as a game-changing technological and cultural process for the construction sector. (Saxon, 2013, p.7)*

The above definition highlights the collaborative premise underpinning the BIM process, which is to provide different people with appropriate access during the phases of the building's complete life, from conception to demolition. According to Ömer Akin, BIM "is one of the most challenging cognitive tasks" (Akin, 2014, p. 17).

BIM is becoming the standard process for delivering architectural projects and its adoption by architectural and construction firms has increased from less than 30% in 2007 to over 70% today (Bernstein, 2014). This is a large change for the architectural industry, and one that is being led by American and British federal and state governments mandating the using of BIM on government building projects to increase the accuracy and unambiguity of construction documentation, to lower construction costs and emissions, and to reduce delivery times.

BIM can be used throughout the entire building life cycle, from the planning and design phase to demolition and heritage. Its use supports the processes of cost management, project management, construction management, and facility operation via collaboration. The industry is still working towards a completely integrated BIM process, one that will be defined in the United Kingdom as Level 3 evolution of BIM (BS 1192:2007, 2008) (Figure 2.1.7). The use of building models developed as a visualisation tool (Kalay, 2004), providing different people with another way to understand the concept and details of a design, helping form a common understanding far more quickly compared with traditional drawings (Eastman et al., 2011). Although clear representation and quality visualisations are crucial aspects of BIM (Gu, Singh, & London, 2014), we can still provide better methods for aiding people to cognise the increasing amount of building information. As the BIM model is now the source of all two- and three-dimensional drawings, design errors and omissions can be identified much more easily before construction than is the case with two-dimensional documentation methods. Conflicts and constructability problems can be detected by comparing each discipline's model information, identifying and resolving clashes before they are identified on site (Eastman et al., 2011).

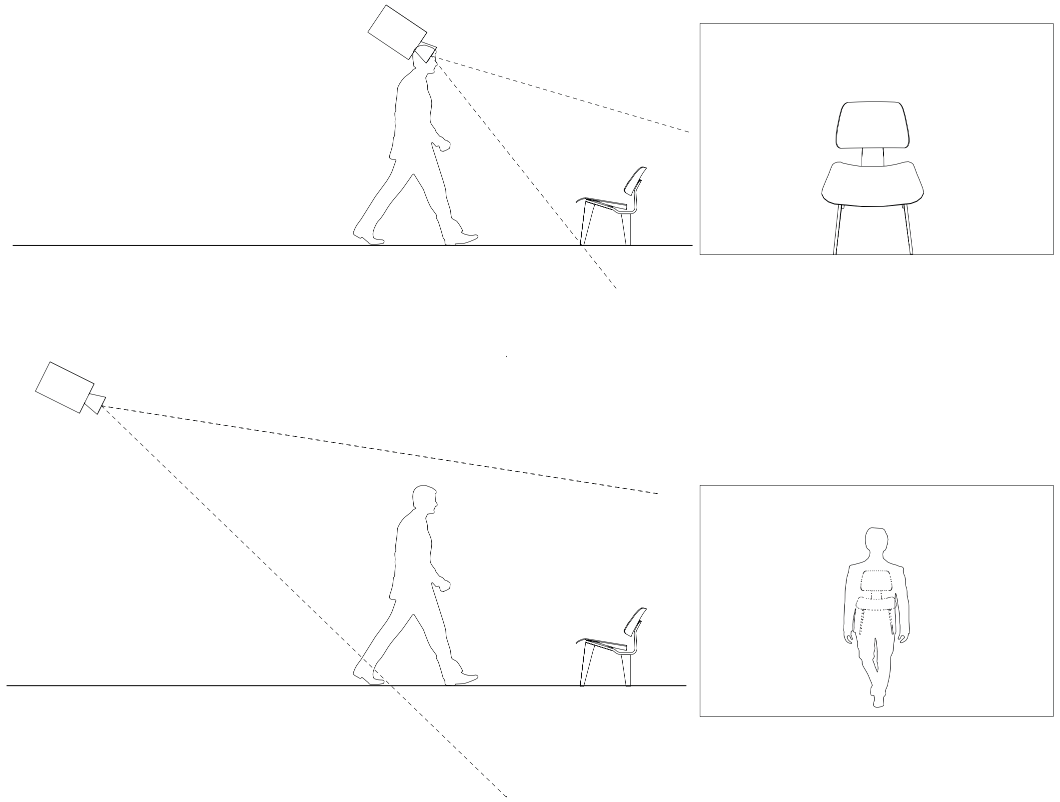


Figure 2.1.8
Location of the virtual camera for (a) first-person perspective and (c) third-person perspective and the resulting views for each (b and d).

Compared with traditional methods, BIM is generating far richer and more productive shared knowledge for many building characteristics. Models are being loaded with multiple dimensions of information, including scheduling, quantity estimation, sustainability, and facility management.
Ömer Akin states that:

> *we cannot deal with these tasks with our tacit and intuitive cognitive skills alone. While the tools and methods at our disposal allow us to explicitly represent all that is needed during the long and tedious design delivery process (i.e., all of the processes and products of design, construction, and facility management) there is nothing intuitive about these tools and their interface functions that are supposed to connect our mental models to the internal functions of the computer code by which they are governed. (Akin, 2014, p. 17)*

For the scope of the research, I focused the project work on computer desktop software, the default platform interface for BIM. I have drawn from the virtual reality and virtual environment research literature. Although considerable research has been conducted on virtual reality, CAVEs are not in common use.

Camera Control

Digital models are viewed via a virtual camera system that is used to control the user's type of projection, field of view, orientation, and movement. "The role of the camera system is to enhance the viewer's experience through its management of the camera's position, orientation, and other properties during interactive sequences" (Haigh-Hutchinson, 2009 p. xxvi). There are two common projections used to represent three-dimensional geometry on a two-dimensional display or plane: perspective and parallel projection. Perspective projection aims to replicate how we view the real world and adds a sense of depth. Parallel projection extends parallel lines of sight from the object to the projection plane, thereby losing the sense of depth for geometric constancy (Glueck & Khan, 2011). With the increasing number of people who are comfortable working in perspective projection (as a result of playing sophisticated three-dimensional computer games) compared with parallel projection, perspective projection is the focus of this research. Such a first-person view offers the closest experience of actually being immersed within a model.

The field of view can be defined as the extent of the projected view affecting the user's perception of a digital model: too narrow or too wide and the view is distorted. First-person and third-person views refer to different kinds of camera control. A first-person camera is set at eye height, representing the user's vision (Figure 2.1.8a), and a third-person camera typically positions the camera behind and above a user avatar, providing an overview into a model (Figure 2.1.8b). Both types of view reduce the degrees of freedom from six

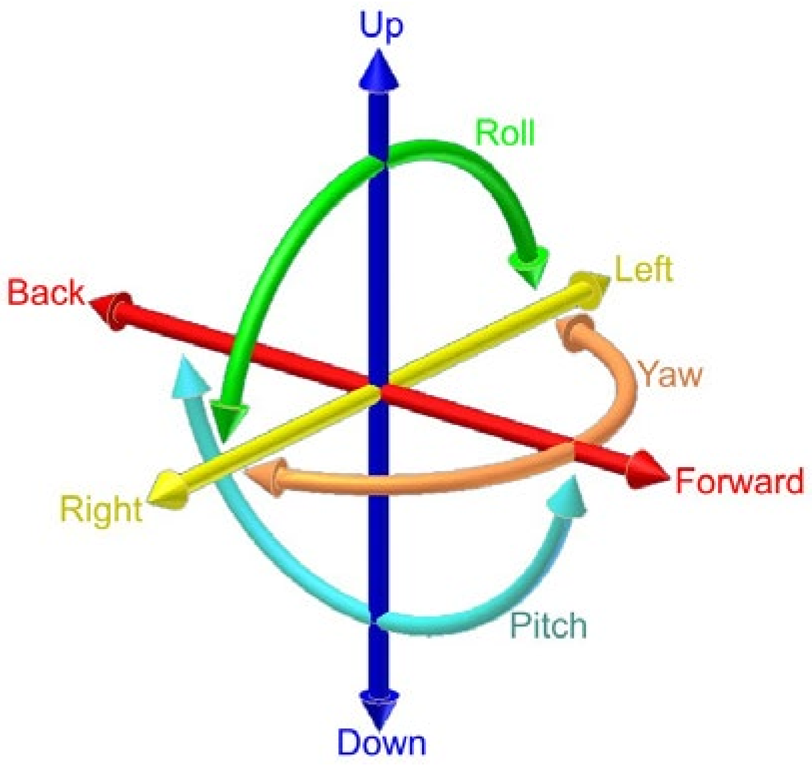


Figure 2.1.9
The six degrees of freedom, namely, forward/back, up/down, left/right, pitch, yaw, and roll that are possible with a virtual camera.

to four, namely, forward/back, left/right, yaw, and roll (Zeleznik & Forsberg, 1999), as shown in Figure 2.1.9. Digital environments are an interactive medium that allows user-control of cameras to navigate. Each camera is moveable, to support user navigation. A common method of camera control and hence navigation is with the WASD keys (on a QWERTY keyboard) for moving the camera, forward (W), left (A), back (S), and right (D), with a mouse to look around, or to control the camera's yaw and roll. Cinematic sequences can be implemented, providing reduced user-control.

Camera control is a challenging problem, and although there is common ground between cinematography techniques and virtual camera systems, real-time digital environments demand different approaches and solutions (Haigh-Hutchinson, 2009). View frustum or clipping planes control the amount of geometry rendered relative to the camera, with near and far clipping planes being used to see inside geometry, as can be seen in the Pathfinder project, a technique not available in cinematography.

There are many different tools for navigating three-dimensional digital models. These tools can be split into two different classes: 'object-centric' navigation and 'space-centric' navigation. During 'object-centric' navigation, the model appears to move inside the scene, whereas during 'space-centric' navigation, the camera moves within the scene and the model appears static. Both classes provide a modal interaction of navigation within a model that has only visual feedback. Users often become disorientated and lost, struggling to control the restricted freedom of movement with which the digital navigation tools provide users, compared with what they are accustomed to.

'Object-centric' navigation uses:
- Pan: moves the view parallel to the model,
- Zoom: enables the magnification of the view of the model to be changed,
- Orbit: moves the camera around the focal point of the model.

'Space-centric' navigation uses:
- Look: rotates the current view vertically and horizontally,
- Walk: walks through the model, by dragging the mouse in the direction in which to move,
- Fly: flies through the model, by dragging the mouse in the direction in which to move.

My research confirms and builds on the investigation by Autodesk Researcher's (Fitzmaurice et al., 2008) to design a safe three-dimensional navigation experience. Autodesk Research define the following seven high-level navigation experience properties:
- Cluster and cache tools;
- Create task and skill-based tool sets;

- Provide orientation awareness;
- Enhance tool feedback;
- Offer precanned navigation;
- Prevent errors; and
- Recover from errors.

"While many existing navigation tools offer some of these properties, it is important to realize the need to provide all of these properties at a rich level to achieve a rewarding navigation experience." (Fitzmaurice et al., 2008, p. 9). Aiding distance estimation is a critical property missing from the above list. No single method or navigation tool will be enough on its own to improve the spatial cognition experience; rather, a closer interconnection is required between the currently available methods alongside further development of the proposed methods investigated in the exegesis.

The computer gaming industry addressed the problem of model fidelity with the application of texture mapping, a method of adding detail by placing raster images onto a three-dimensional model. The method was pioneered by computer scientist Edwin Catmull (Catmull, 1974), and refined by James Blinn and Martin Newell (1976). Texture mapping, as described by Professor Yehuda Kalay, "consists of displaying a scaled and properly oriented image of some texture (e.g., timber grain, brick, or concrete) on the screen where the otherwise featureless face of an object would be displayed" (2004, p. 174). Texture mapping is required to render geometry in most three-dimensional computer game engines, and is often the only visual rendering of the model geometry. This contrasts with BIM software in which the geometry is rendered as lines and shaded surfaces. Texture mapping provides a two-fold benefit of graphic processing optimisation and the appearance of detailed model definition. The real-time rendering processes of computer game engines are fundamentally different from those used by leading BIM software. Although texture mapping can represent a material such as brick, it may not be in correct alignment, confusing the detail. An analogue comparison is the hatching used in section drawing, a graphical method for describing a material. Computer games usually tend towards realism representation, whereas architects have favoured graphical representation.

Section Summary

The improvement of spatial cognition inside digital models requires an understanding of how people create, store, and utilise cognitive maps to enable wayfinding and navigation, supported by methods of wayshowing and pathfinding. Also of importance is the continuing evolution of architectural documentation and its connection with technology, which has progressed from verbal instructions to multidimensional digital models now requiring complex camera control techniques that dictate how we experience the interiors of digital architectural models, often sending people into moments of whiteout.

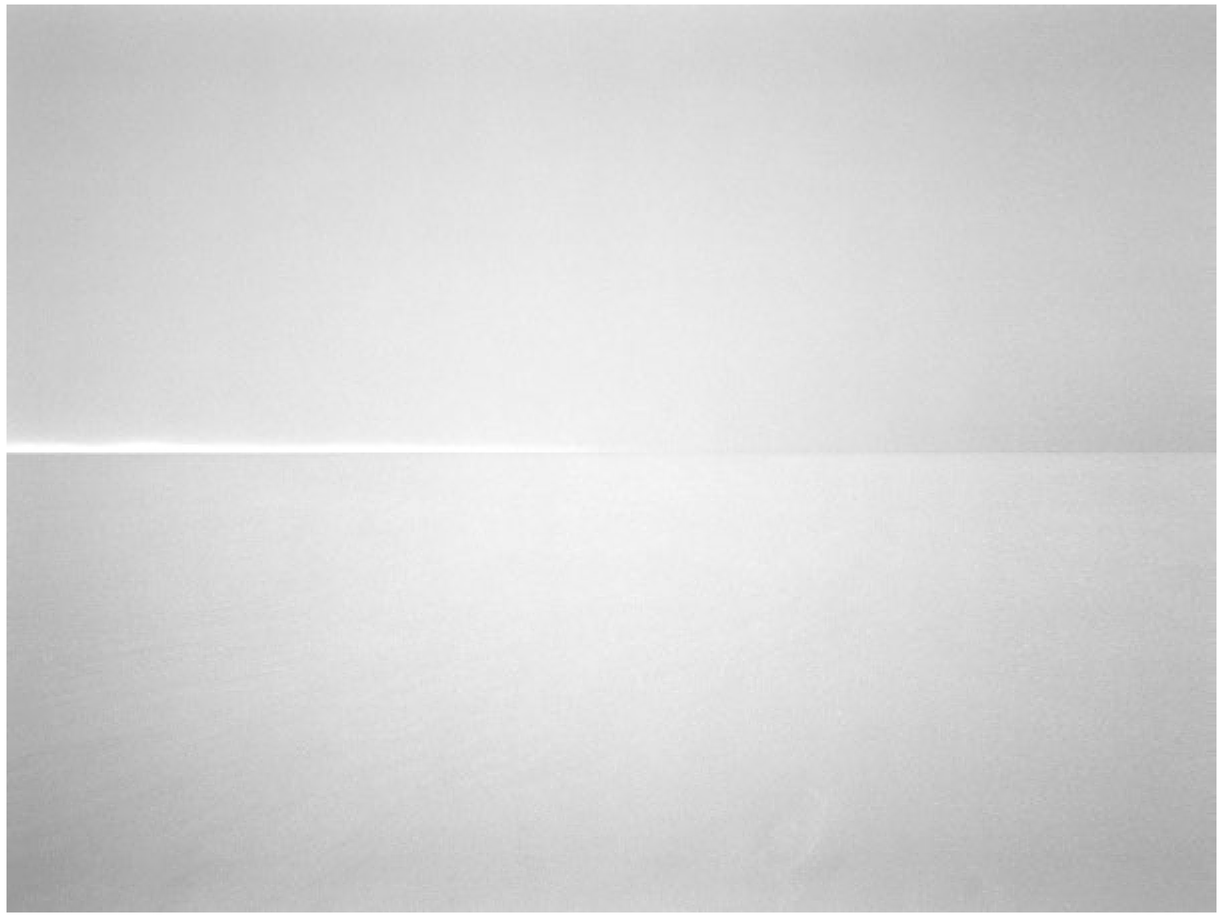


Figure 2.2
Antarctica: The Grain of White #26, Anne Noble, (2009).

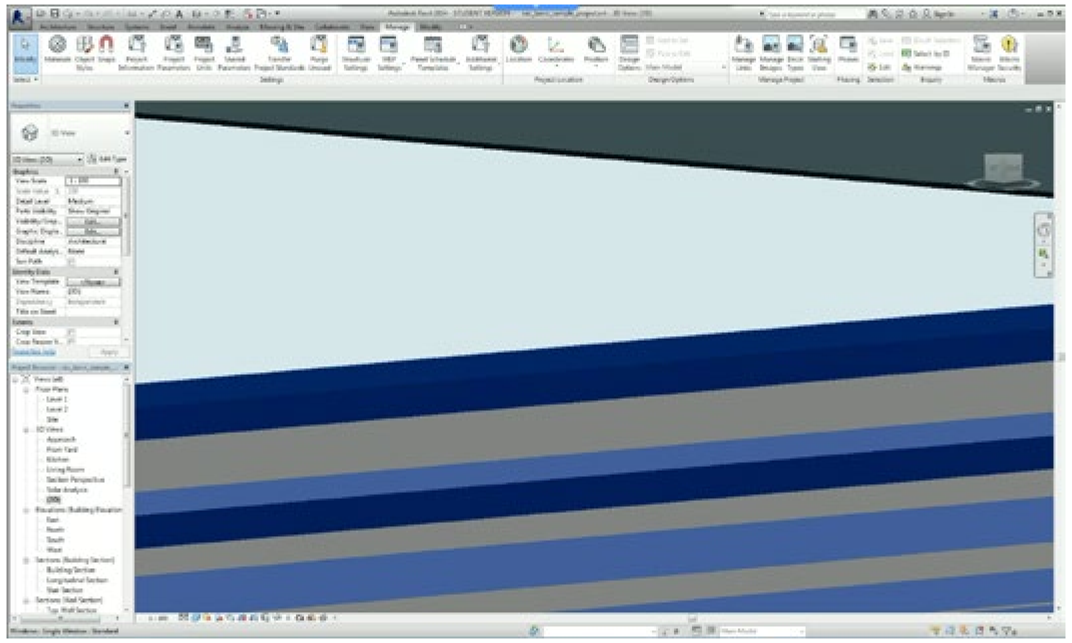


Figure 2.2.1
A screen capture at the moment of being lost inside a digital architectural model. Revit 2014 Architecture sample model lost while orbiting, with ViewCube, inside the interior of the model.

2.2 Research Method

In this section, I outline the method of design research by project that I used and the research tools that enabled an investigation to be made of spatial cognition within digital architectural models. As a spatial information architect, the projects followed architectural design research strategies in the search for improving spatial cognition inside digital models.

Getting lost inside three-dimensional digital models is a common and frustrating problem that has seen only gradual improvements over time. Even experienced people can become disorientated or unsure of how to find a specific location within a building model. Flann O'Brien wrote in his novel 'The Third Policeman' that:

> *the continual cracking of your feet on the road makes a certain quantity of road come up into you. When a man dies they say he returns to clay but too much walking fills you up with clay far sooner (or buries bits of you along the road) and brings your death half-way to meet you. It is not easy to know what is the best way to move yourself from one place to another. (O'Brien, 1967)*

The quote reflects how navigation within digital architectural models can affect one's perception of a building design, and illustrates how frustrating relocating or adjusting a camera can be, causing conditions of whiteout (Figures 2.2 and 2.2.1).

Quantifying and qualifying spatial cognition can be difficult, as it is manifest in a personal mental image or cognitive map, and the information needed for one person to comprehend a space could be completely different to that of another person. Perhaps because it requires all of our senses, spatial cognition is still not completely understood (Montello, 2001; Tversky, Morrison, Franklin, & Bryant, 1999). Research applied to spatial cognition in complex spaces typically surveys "navigation, a complex behaviour that combines the physical act of locomotion with a suite of cognitive abilities such as place memory, imagery, and planning. The cognitive components of navigation are sometimes collectively referred to as wayfinding" (Waller & Nadel, 2012, p. 5). A considerable amount of research into spatial cognition and more specifically into navigation has been conducted in the field of psychology, where typically clinical and comparative studies are analysed (Foreman & Gillett, 1998). In the context of my research, via design practice, I require other research methods beyond those used by psychology and computer science.

My exegesis is positioned as design research by project, in conjunction with the critical review of literature made in Section 2.1. As discussed in the introduction chapter, the methodology involves a reflection-in-practice process of designing via making, based on what Donald Schön considers designing as a reflective conversation with the material of a situation (1983). The Translation projects for example, see section 3.1 Translation Projects, provided insight possible by creating and critically reflecting within these projects. This project-based research is conducted and rigorously evaluated to extend current design knowing and knowledge of improving spatial cognition inside digital architectural models. The projects are design explorations that test concepts of navigation within digital architectural models and, as Peter Downton explains, are not “intended to produce a fully pre-conceived outcome, rather it is expected to produce change in the existing situation and hopefully offer fresh surprise and delight” (2003, p. 6). The Navigation projects for example, see section 3.2, are explorations of different navigation support. As a derivative of action research, David Wilkinson (2002, p. 4) defines action research as “diagnosing a specific problem in a specific setting and attempting to solve it. The ultimate objective is to improve practice in some way.”

Practice as creative-making activity is an “explicit and intentional method for specific research purposes” (Gray & Malins, 2004, p. 104) through design and reflection. The creation and reflective testing experimentation of interfacing with three-dimensional building information resulted in a range of ‘approximations’ that built towards a more resolved framework. The process of reflection is embedded within the projects, which were evaluated during the designing, making, and testing, thereby informing the next project. The material is the interface of navigation and wayfinding. By ‘making’ within the context of selected literature and related work, this formed a crucial quest for new knowledge in my research.

My research is situated in terms of an interface of spatial experience in wayfinding (as Mollerup (2013) defines wayfinding) of digital architectural models, and not in terms of the typical view of architecture (that of a completed building design proposal). This also differs from the fields of psychology and computer science (human–computer interaction).

Research Instruments

Research instruments, as defined by David Wilkinson and Peter Birmingham (2003, p. 3), are “simply devices for obtaining information relevant to your research project, and there are many alternatives from which to choose.” My research makes use of many instruments that feed into the projects. A number of tools have been used previously for measuring navigation within virtual environments. With respect to this, Rudolph Darken and Barry Peterson outline the acquisition of spatial knowledge and representations of spatial knowledge as arguably the most important and least understood of such tools (Darken & Peterson, 2001, p. 497). This representation of spatial knowledge, or cognitive map, is affected by the methods of acquisition, whether acquired from exploration and navigation or from plans and maps. The present research is concerned with exploration and navigation, while acknowledging the influence that drawing projections have on the construction of cognitive maps.

The projects are simultaneously method, instrument, and result, defining and progressively informing my research and acting to triangulate an understanding of wayshowing that goes beyond simply measuring the time taken to navigate to a location. This allows multiple research methods to be used to triangulate results beyond a single method. The development of the projects has been influenced by the continual evolution of software, which both enabled and restricted the explorations. Each project has been informed by the capabilities of the software used.

Given the gamut of issues relating to spatial cognition and digital models, the projects developed after critical reflection both during and after each project. Although the projects may be atypical, they all offered important learning and qualitative information (Denzin & Lincoln, 2011). Each project tested a range of concepts and issues and informed the other projects and the rereading of itself.

The Translation projects are an exploration of the working drawing conventions of section and exploded axonometric within a three-dimensional interactive digital model. The projects investigate how we can engage with model geometry within a digital architectural model. Testing was trialled on active architectural projects with productive failings, as discussed in Section 3.1. The Translation projects tested the concept of interactive drawing conventions, firstly as design explorations of the interface with the technology, and then with two different live architectural projects to confirm findings. The projects tested the implications of the interactive control of drawing conventions within a digital environment, cross-checking against possible problems. Projects Section Pavilion and Layer Pavilion enabled the concepts of translation to be sketched or tested. The Victoria Quarter Building 6 and Pekapeka projects tested the implications of workflow and interaction of navigating drawing conventions in digital models. Critically reflecting on the projects both during and after their making and testing phases allowed a rigorous process of evaluation to be established.

The Navigation projects test other ways of navigating digital architectural models beyond the typical digital navigation tools and methods for exploring the interior. AI pathfinding was used to guide people between locations, whether with set nodes or floating locations, as outlined in Section 3.2. The set of projects explored the implications of input for enabling spatially aware navigation modes, ranging from mouse or finger control to motion sensing. Each project tested the implication of the impact of interaction on

Translation Projects	Navigation Projects	Distance Projects
Section	Pointer	Te Ara Hihiko
Layer	Pathfinder	Odograph
VQ6	Space Trace	Your Grid
Pekapeka	Show Me	Measure
Research Methods Used		
Case study	Case study	Case study
Experimentation	Observation	Experimentation
Critical Reflection	Questionnaire	Exploration
	Experimentation	Critical Reflection
	Critical Reflection	

Table 2.1
Diagram of research methods in each group of projects created for this research.

the navigation interface. The four projects develop spatial transitions, with each project responding to the previous one. The Pointer project tests direct inter-location teleporting; Pathfinder project introduces and tests building responsive AI pathfinding and changing soundscapes; Space Trace introduces motion sensing of the physical environment to control navigation; and Show Me develops AI pathfinding, including an agent that leads the way to a given location and the display of location-aware metadata. The projects develop and begin to push the boundaries of spatially aware transitions by critically reflecting on each project, including the preceding projects.

The Distance projects provide explorations of assistive interfaces for spatial cognition and awareness that aid in the estimation of distance within digital architectural models. Both egocentric and exocentric distance comprehension improve how we navigate and wayfind. Previous research has focused on unaided experiments in virtual environments of distance estimation. The projects in the present research explore methods of assisting people to improve distance and scale awareness, as described in Section 3.3. Each of the four projects investigates methods of aiding distance awareness: Te Ara Hihiko critiques the mouse walk tool by providing different levels of guidance; Odograph records and displays total and last distance travelled, aiding in the spatial comprehension of a building; Your Grid develops a spatially aware personal grid that is overlain at current floor level, aiding distance estimation; and Measure investigates a quick dimension tool that allows fast and intuitive display of distance. All four projects interrogate methods of aiding spatial cognition via improving distance comprehension. Each project tests the implications of different modes of understanding distance while critically reflecting on all of the previous projects.

This research draws on multiple research methods (table 2.1) to piece together the project work, interrelating each experimental design investigation through a range of digital model interfaces. The projects are, as stated in the introduction chapter, simultaneously method, instrument, and result, defining and informing my research. This is key in describing my method, which is not linear in process, although the projects are described in this exegesis in a linear chronological order. I would argue that the research method is reflective in a non-linear and non-chronological sequence, and that it allows a rich, open, and critical understanding to be developed of the research conducted. I have structured the projects in chronological order of completion, because this clearly indicates the physical development of each project. The findings, as discussed in Chapter 4, respond to critical reading across all of the projects, with investigations incorporating testing at a single moment and testing across all the projects. Running multiple projects enabled me to triangulate the findings across the various scales and types of projects.

Criteria for Evaluation

This research is evaluated by following on from the work started by Kevin Lynch in 1960. Romedi Passini (1984) described wayfinding and architectural design concepts, which were extended by Per Mollerup in 'Wayshowing' (Mollerup, 2005). However, none of the books offers a discussion of evaluation methods. Previous research into spatial cognition has provided a valuable understanding of spatial skills approached from psychometric and experimental methods underlying cognitive process (Casey, 2012); however, such research lies outside the scope of the present research and evaluation methods.

My exploration of possible research instruments exposed the limitations of those used by Doug Bowman et al. (1998, p. 126), including that a memory task for information gathering within an immersive virtual environment may not give a clear response of the navigation modes. Sketching cognitive maps was rejected because a cognitive map is constructed of multiple sensual inputs that are impossible to capture in a sketch, which typically defaults to a plan and can be limited by people's perceived drawing ability.

The condition of whiteout as defined in Chapters 1 and 2 explains the loss of subtle cues we use in spatially orienting and locating ourselves. The concept of whiteout is the base criterion used in evaluating the project work: how does each project improve spatial cognition and reduce the incidence of whiteout? Within in architectural digital models, whiteout moments are the times you become stuck, the information you want is obscured, often resulting in frustration. As my research progressed, becoming more focused, each project required the criteria of evaluation to focus on the specifics of that project. For instance, the Te Ara Hihiko project used the work of Bowman, D. A. et al. (1998) paper A Methodology for the Evaluation of Travel Techniques for Immersive Virtual Environments, allowing a range of criteria across different conditions to be evaluated. To understand a building spatially, we need to experience moving inside the structure. To move within digital models, where moments of whiteout are common, we need to navigate the unknown. John Huth's (2013) three elements of navigation give clues to aid experiencing digital models. I believe that spatial orientation (Fitzmaurice et al., 2008; Ziemek et al., 2012) and location awareness (Luo, Luo, Wickens, & Chen, 2010) have adequate solutions already, although whether they are being utilised is beyond the scope of the present research study. In contrast, the estimation of distance inside digital models is poorly supported, which suggests that aiding distance cognition will improve navigation and reduce moments of whiteout

Using a questionnaire in the Te Ara Hihiko project provided qualitative responses to wayfinding tasks, asking people to rate spatial awareness different navigation support provided while searching for different locations within a digital model. Although not connected to an output of a project, my observation of a clash detection meeting at the office of Cahill Contractors in San Francisco on June 10, 2013 was insightful regarding people's lack of location awareness during working with a BIM model.

The Distance projects in Section 3.3 were directly informed by blind architect Chris Downey, which aimed to discover the methods of navigation and wayfinding used by a once-sighted architect. Chris Downey is in the unique position of being a blind practicing architect. Chris uses touch and sound to help orientate and locate himself while walking (Downey, 2013). His understanding of distance is critical in knowing when to change direction. He has to rely on non-visual senses to build guiding systems and to estimate distance.

This section of Chapter 2 has explained the research methods considered and used to better understand spatial cognition via navigation inside digital models. The projects are not necessarily completely representative of how we navigate and gain spatial cognition inside digital models; however, this collection of projects, which includes both typical and atypical approaches, has led to a better understanding of navigation methods by exploring key challenges of spatial cognition inside digital models to aid distance estimation and to reduce moments of whiteout.

Figure 2.3
Antarctica: The Grain of White #27 by Anne Noble, (2009).

2.3 Related Work

My research sits uniquely as an architecture-based practice within a domain typically dominated by computer science and psychology. Initial research dealing with navigation of virtual environments was conducted by computer scientists exploring the potential of the technology. Psychologists have used virtual environments to help understand spatial cognition by replicating real-world scenarios. Aiding distance estimation inside BIM models is the original contribution to knowledge on which my research is focused. Within the field of virtual environment navigation and wayfinding, research has addressed methods of providing or supporting spatial orientation and location awareness. The only prior distance-related work I could find is that regarding the accuracy of people's estimation of distance in virtual environments as discussed further in this section. My research has developed from a frustration with navigation methods within complex building model, and the research includes investigations of how working drawing conventions may translate into three-dimensional virtual environments, and methods of assisting wayfinding (wayshowing) to aid distance estimation.

Navigation Tools

In 1993, Ruby Darken and John Sibert wrote 'A Toolset for Navigation in Virtual Environments'. Their research is important on account of the period in which it was conducted, which was during the early stages of virtual reality. It is of only partial benefit for the present study, as it is not directly related to desktop environments, but the toolset covers the major methods still used for navigation today. The toolset makes reference to Lynch's (1960) generic city wayfinding component categories: paths, edges, landmarks, nodes, and districts. The toolset includes the following navigation techniques:

- Flying,
- Spatial audio,
- Breadcrumb markers,
- Coordinate feedback,
- Districting,
- Landmarks,
- Grid navigation, and
- Mapview.

Darken and Sibert (1993) conducted an informal study of the effects of the navigation tools, and found that the tools had a strong influence on people's behaviour. The concept of flying as a navigation tool is weak, really offering a change in travel or motion control that then enables a change in viewpoint. The spatial audio scenario is a crude but promising condition that was conceived of as an acoustic landmark. This offers little on its own as it requires a minimum of stereo speakers to operate productively. Considering the spatial audio beyond an acoustic landmark to represent spatial sound qualities or reverberation within digital architectural models deserves further research outside the scope of this exegesis. The breadcrumb markers offer a useful method to find one's way home and to help with building a cognitive map, but can cause information overload in the environment. A breadcrumb marker also offers a method of providing a path to follow, which I discuss further below. The use of districts and landmarks is important when designing a building and a virtual environment. However, these features become less useful within designed architectural digital models.

Darken and Sibert's (1993) work addresses the design of the virtual environment that should be translated into the architectural design, not the navigation interface of digital architectural models. Owing to the increased degrees of freedom available within these models, providing additional clues to aid navigation is key, providing wayshowing to support wayfinding inside the models. Their research does not address distance estimation in an easily accessible way; coordinate feedback and mapview provide abstractions of distance, forcing people to calculate distances, a conceptual shift for most users. Spatially, the environments used in their study ranged in density, but were confined to a flat surface on one level, and did not address the subject of a complex multifloor building interior as is required to comprehend a digital architectural model.

Industrial engineers Jui Lin Chen and Kay Stanney proposed a theoretical model of wayfinding for the design of navigational aids in virtual environments (1999). The model is based on wayfinding strategies in physical environments. They presented a navigational tool taxonomy that classifies the tools into five functional categories:

- Display an individual's current position,
- Display an individual's current orientation,
- Log an individual's movements,
- Demonstrate the surrounding environment, and
- Guided navigational systems.

Making a comparison with John Huth's three key elements of navigation, which are "spatial orientation, the ability to estimate distances, and find position from environmental clues" (Huth, 2013, p. 8), we can draw direct connections to Chen and Stanney's tools that display current position and orientation, and both are available in commonly used BIM software. The success of the specific implementation of these two tools can be questioned, but this lies outside the scope of the present research study. Tool number three, logging an individual's movements, is now commonplace with the use of smart phones in the physical environment. Although logging an individual's movements is possible in BIM, there has been no known implementation, and this is explored in Chapter 3. Chen and Stanney suggest that "if the design of a virtual world lacks critical clues (such as direction and distance) and the time spent in the virtual environment is relatively short, then skills that are readily applied in the natural world (such as distance estimation through exploration) may be lost in the virtual world" (Chen & Stanney, 1999, p. 672). Chen and Stanney do not identify a tool type that directly aids in the estimation of distance.

Chen and Stanney divide wayfinding and navigation into three interconnected processes:

- Cognitive mapping and information-generating,
- Decision-making process, and
- Decision-execution process.

This is a simplified version of Per Mollerup's ten-step wayfinding process (Mollerup, 2013, p. 22) discussed in Section 2.1. The key point is the quality of the virtual environments: the previous studies mentioned (Darken & Sibert, 1993; Chen & Stanney, 1999) reported research that was conducted in the mid- to late 1990s, and the models would be considered extremely crude today. The models lacked architectural detail, both modelled and textured, and this cannot be underestimated in aiding spatial cognition. Within BIM models, a similar conclusion can be made with models containing only simple architectural details, beyond building items like stairs or small spaces such as toilets. People can still become lost in these spaces, even with room labels:

> *It should be pointed out that environmental models used in many navigation research studies were abstract or simplified and lack rich spatial information about three-dimensional objects (e.g., realistic appearances of landmarks). Such an abstraction could be less efficient to help users remember the successive locations in navigation. Although creating more realistic and detailed virtual environment models is time and labor consuming, it ensures the model fidelity, which is crucial to the generalisation of research results (Darken, Allard, & Achille, 1998). Therefore, it is necessary to study navigation behaviours in environments with feeling of presence and more detailed spatial information, such as rich textures and realistic objects for wayfinding guidance (e.g., a virtual sun or architecture shades). (Wu, Zhang, & Zhang, 2009, p. 3)*

Janki Dodiya and Vassil Alexandrov (2008) reaffirmed that efficient navigation is an essential element of successful virtual environments. Those authors investigated nonspeech auditory navigation aids including audio landmarks and music for fast identification of different locations. Both the Pathfinder and Space Trace projects explore the use of auditory navigation aids (Section 3.2).

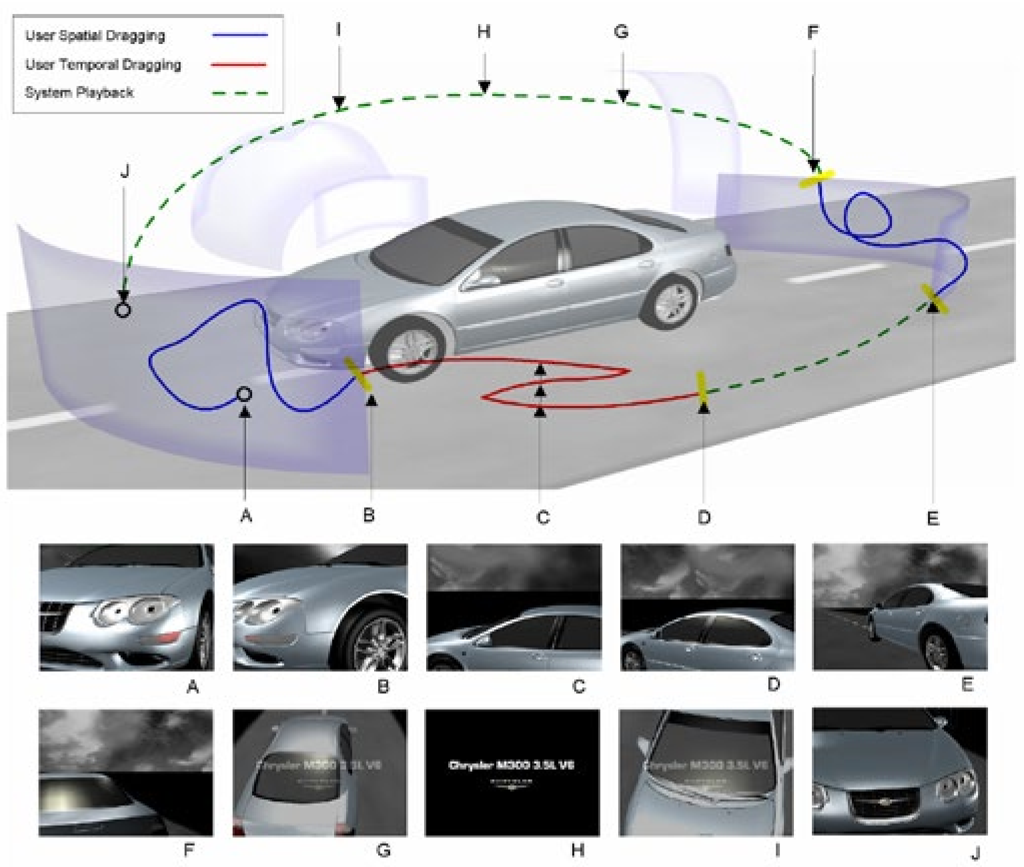


Figure 2.3.1
StyleCam, an example of authoring 3D viewing experiences. Top: system components and their reaction to user input. Bottom: what the user sees.

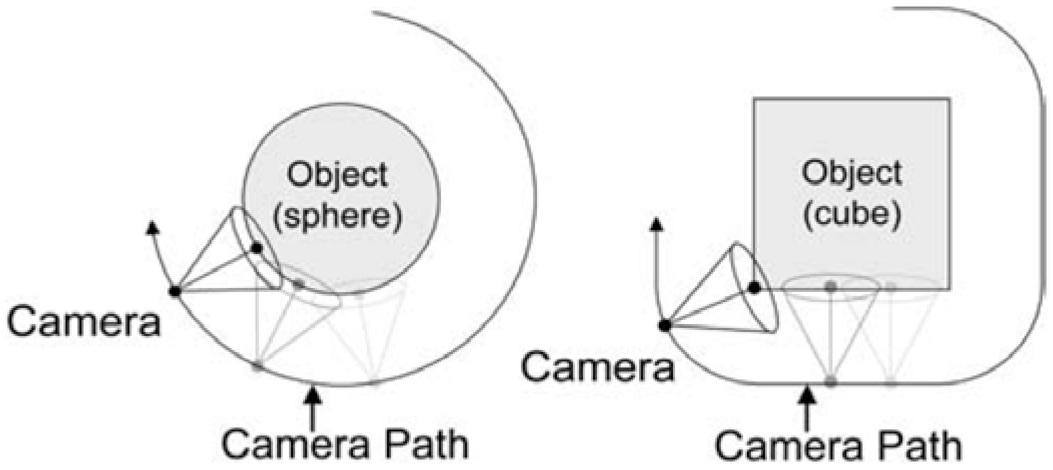


Figure 2.3.2
Detail explaining HoverCam's interactive three-dimensional navigation. A camera path is inferred based on a model's geometry.

Spatial Orientation

Autodesk (previously Alias|Wavefront) researchers have published several research papers that address the navigation and viewing of digital models. Those researchers noted the difference between authoring and reviewing digital models, and although the focus of my research is the latter, both could be considered as wayfinding tasks, requiring different understanding of the navigator. Key research projects by Autodesk researchers include StyleCam (Burtnyk et al., 2002), HoverCam (Khan, Ben Komalo, Stam, Fitzmaurice, & Kurtenbach, 2005), and ViewCube (Khan et al., 2008), all of which address methods of viewing three-dimensional models and aiding the navigation processes. StyleCam proposes fixed areas within which cameras are contained, with a normal lock on the surface of the model, preventing users from becoming lost and allowing limited control, and linking views with a spatial transition (Figure 2.3.1). There is a clear trajectory from the StyleCam to the HoverCam, that of an interaction technique for navigating around three-dimensional objects in proximity, by intelligently integrating camera controls for tumbling, panning, and zooming (Figure 2.3.2). The HoverCam automates the process that the StyleCam introduced by using a small set of constraints, including collision detection, to maintain a hover distance from the object. This enables a person to avoid becoming too close to the model and entering a whiteout condition. The HoverCam raises an interesting solution to the problem of becoming lost when the observer is so close to the geometry of a model that they are unable to see anything else. Of the three Autodesk Research projects, ViewCube is the only one to have been implemented into commercial software, as a three-dimensional orientation indicator and controller. "When acting as an orientation indicator, ViewCube turns to reflect the current view direction as the user re-orients the scene using other tools. When used as an orientation controller, ViewCube can be dragged, or the faces, edges, or corners can be clicked on, to easily orient the scene to the corresponding view" (Khan et al., 2008, p. 17). ViewCube provides an indication of orientation of the exterior of a model, greatly improving spatial cognition. ViewCube offers a reduced amount of feedback within the interior of a building model, and provides little improvement in spatial cognition inside a model.

The three above-mentioned Autodesk Research projects clearly aid spatial orientation, ViewCube in particular. Both StyleCam and HoverCam are referred to as navigation tools by the authors; however, as a result of focusing on an exterior view of an object, those two tools provide aid in spatial orientation and to a lesser degree in locating one's position. They provide no clues to estimating distance within a model. Another study by Autodesk Research (Glueck, Crane, Anderson, Rutnik, & Khan, 2009) is discussed further below within this chapter and investigates distance estimation with a multiscale reference grid.

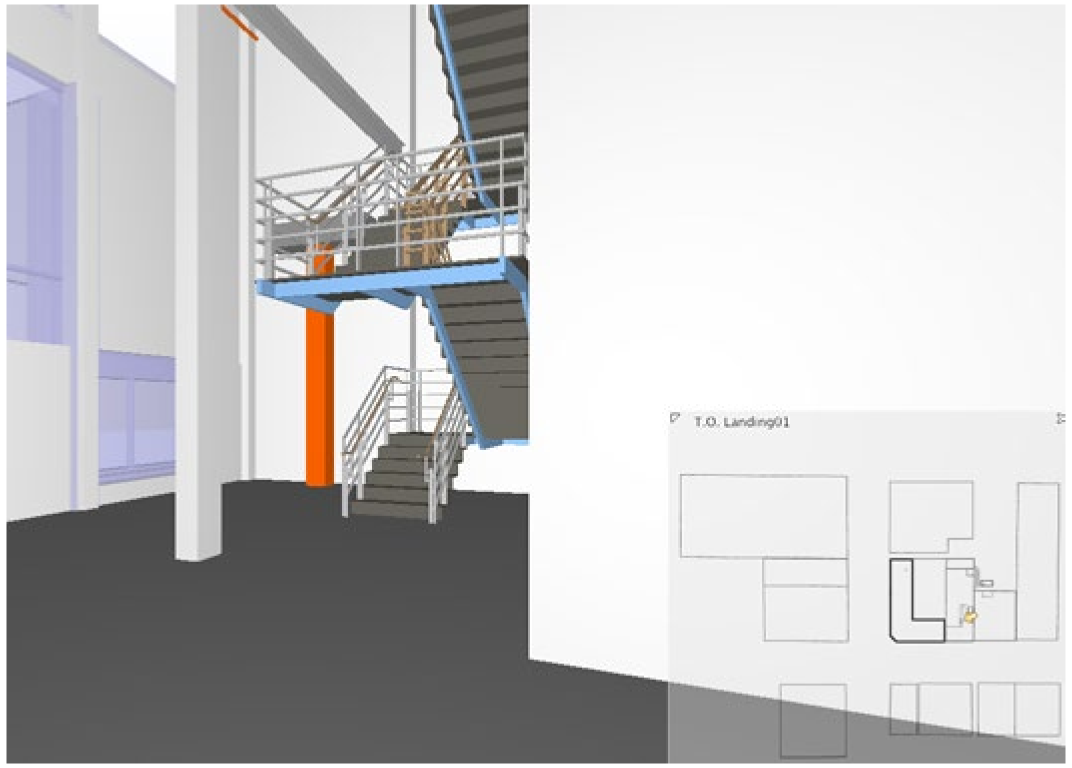


Figure 2.3.3
A perspective view of a digital architectural model with location plan (lower-right-hand corner), locating the viewer within the context of the building's site plan.

Location Tools

An accurate awareness of one's location or position is a key component of navigating in both physical and virtual environments. In the physical world, maps have existed to help in locating ourselves for many centuries. More recently, GPS devices have provided people with an accurate way of knowing exactly where in the world they are, and have drastically changed methods of wayfinding and navigation. However, current GPS technology is unable to accurately locate people within buildings (although this is in the process of changing, with indoor positioning systems able to actually locate people inside a building (Curran et al., 2011). Two-dimensional maps were some of the earliest navigation aids within virtual environments (Darken, 1993), Figure 2.3.3 shows an example of in-view map. Professors of computer science Luca Chittaro and Subramanian Venkataraman compared two- and three-dimensional map aids for navigation in multifloor digital buildings (2006). Both types of map provide information about the position of objects in the environment with respect to the user's position. The maps were located below a first-person view-port into the building model. The study concluded that the more familiar two-dimensional map produced better performance for wayfinding tasks. The quality of the model was a simplistic representation of a real building, which could limit people's spatial understanding because of the lack of building detail. Section 3.2, Navigation projects, explores the use of in-view maps, for which commercial BIM viewing software Solibri model viewer and BIManywhere, for example, provide the option to have a map view showing the current location and orientation of the user, aiding spatial cognition in the BIM model.

Human–computer interaction researchers Anna Wu, Wei Zhang, and Xiaolong Zhang (2009) evaluated three wayfinding aids in a virtual environment: human–system collaboration, animation guide, and view-in-view map. The results showed that the in-view map clearly provided the most benefit of the three aids studied for easy and medium-level tasks, and that the animated guide and view-in-view map performed equally for complex tasks. The study concluded that "people can benefit from tools that provide more spatial information across different scale levels and tools that help spatial information integration" (Wu et al., 2009, p. 19). The environment in the study of Wu et al. was limited to a simple cityscape, so only two-dimensional navigation was observed; the authors proposed further study of more complex environments and tasks. The research of Wu et al. did not investigate distance cognition in aiding navigation. In an effort to maintain the focus of my research, I selected not to explore multiple views of the same model, beyond view-in-view maps. Although CAD software commonly provides elevation, sectional, plan, and perspective views simultaneously, which can benefit the creation of digital architectural models, the focus of my research is on completed models.

Distance

Psychologists Adam Richardson's and David Waller's research project entitled 'The Effect of Feedback Training on Distance Estimation and Virtual Environments' (2005) consisted of two experiments that examined observers' ability to use error-corrective feedback training to improve the accuracy of judgements of egocentric and exocentric distances. Richardson and Waller state that "estimates of absolute egocentric distances (those from an observer to an external object) are commonly underestimated by as much as 50%" (2005, p. 1089). The reasons for the under-estimation of egocentric distances are still not fully understood. Examples include the limitations of head-mounted displays, the field of view, the resolution and quality of images, and the lack of stereo two-dimensional imagery. Head-mounted displays are currently very rarely used in BIM processes. These technical reasons for poor distance estimation are still relevant to desktop software. The study of Richardson and Waller was made within a stark virtual environment that offered little in the way of cues or detail to help with understanding the scale of the model. A key point that was not mentioned was the significance of having items of known size that provide a reference to help understand scale and distance. The authors explain the importance of accurately estimating modelled distances in virtual environments and argue that poor distance cognition limits the technology. The authors make explicit the importance of further research, beyond training. I believe that providing other forms of information to help understand scale inside virtual environments will improve spatial cognition, navigation, and distance estimation.

The work of Andre Brown and Michael Knight with the NAVRgate is situated within a virtual reality environment that uses a bicycle and scooter as methods of locomotion interaction (Brown & Knight, 2001; Knight & Brown, 2003), something that is not practical for BIM interaction. By using an input device that differs from touch, mouse, or keyboard, both of the Brown and Knight studies explore methods of calibration in an attempt to aid distance estimation.

Does the quality of computer graphics matter when estimating distances in virtual environments? In all virtual environments, there is a compression of egocentric distance. As a result, estimations of absolute egocentric distance in virtual environments are unlikely to be aided by photorealistic improvements in computer graphics, such as better texturing and illumination (Thompson et al., 2006). A number of investigations by Betty Mohler and co-workers address the influence of providing visual feedback on egocentric distance estimation (Mohler et al., 2006; 2010; Mohler, Bülthoff, Thompson, & Creem-Regehr, 2008). However, none of the studies raises the concept of techniques that aid distance cognition, improve distance estimation, and aid navigation.

Autodesk Research (Glueck, Crane, Anderson, Rutnik, & Khan, 2009) demonstrates a multiscale reference grid with position pegs to solve depth cue problems in principally parallel projection and perspective projection. Their paper outlines the use and implications of static grids in authoring software, which are typically fixed at the origin of the software space and may not relate to the building or the viewer. Many difficulties occur in three-dimensional interactions: being inside versus outside, the relationship between viewpoint and object, what is the user's focus, projection methods, and what is the user's task (from authoring to reviewing)? Because of such complexities, Autodesk Research chose to "focus on the particular area of exterior views of multiscale three-dimensional scenes in both parallel and perspective projections in an authoring application setting" (Glueck et al., 2009, p. 226). Although unable to locate any literature investigating the most effective grid characteristics, Glueck et al. describe the desirable grid qualities for supporting depth cues: occlusion, relative size, and height in the visual field. The multiscale reference grid described lies only on a conceptual two-dimensional ground plan that dynamically alters scale relative to camera position. So, if one is viewing at a city scale, the grid will be drawn at 1 km major and 100 m minor divisions and if viewing a car the grid is represented at 1 m major and 10 cm minor divisions. Although this would be productive in the authoring of three-dimensional content, it would be easily misread in reviewing a BIM model. The grid is located only as a conceptual ground plane, and once inside a building there is a high possibility of not being able to view the grid and hence losing its benefits. Further research with the use of grids, again fixed at ground level, has shown improved depth perception (Hartzell, Thompson, & Kim, 2012), although that study was situated within a rather barren landscape, and it did not address the effects of depth perception within the interior of a digital model. In Section 3.3, an egocentric grid is explored to aid in distance estimation, whereby Your Grid imparts important design considerations for three-dimensional reference grids in presenting relative scale and object location.

Figure 2.3.4
An example of the rendering qualities that are possible in real-time three-dimensional game engines, showing a screen capture of 'Rsye: Son of Rome' developed by Crytek (2013).

Figure 2.3.5
Screen capture from Disney Infinity (video game) with a navigation aid, a green arrow pointing through an impassable building to require location, and with which the player can navigate around the building.

Digital Architectural Models

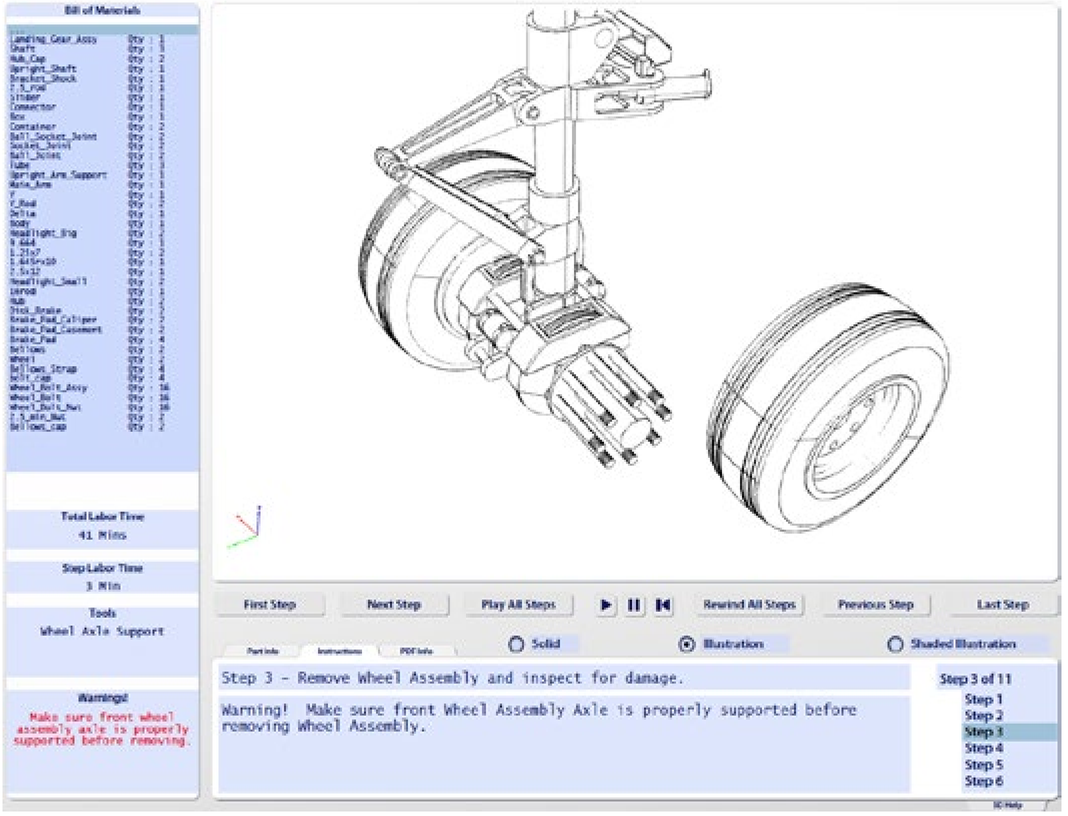
The construction industry, including design, engineering, construction, and operation, is the most important user of digital architectural models, followed by the computer game industry. The automobile and aerospace industries also utilise three-dimensional digital models with interior inhabitation.

The computer gaming industry has developed and utilised many approaches to improving navigation and spatial awareness in virtual environments, including realistic texturing, lighting, direction indication, mini-maps, optimal path, and heads-up display. Popular first-person-view games are constructed with a walking or driving metaphor of camera motion. According to Azam Khan et al.,

> *this metaphor suggests many things: there is a ground plane, the viewpoint is somewhat above the ground, camera rotation is egocentric, there is notion of which way is "up", etc. These constraints simplify camera motion from a general 6 degrees of freedom problem to almost 2 degrees of freedom problem. Further constraints, such as collision detection, prevent the camera from passing through walls, characters, and objects in the scene. This entire set of constraints is needed to convey the walking camera metaphor (2005, p. 73)*

In their article 'High Quality Navigation in Computer Games', computer scientist Dennis Nieuwenhuisen and co-workers state that "navigation plays an important role in many modern computer games" (Nieuwenhuisen, Kamphuis, & Overmars, 2007, p. 91). Often, the design of game play affects the required navigation, featuring unidirectional structured pathways with limited exploration. Their article sets out an AI-based method that computes a roadmap of smooth, collision-free navigation paths for navigation of an entity, the motion of a group of entities, and smooth camera movements through an environment. Bernadette Flynn begins to distinguish "a shift in importance from narrative to geography" (2003, p. 4) within computer games; with regard to this, Figure 2.3.4 shows an example of the quality of real-time computer game rendering, providing a sense geography. These studies are directed towards the design and construction phases of a game, outlining algorithms and experiences that are beyond the scope of my research.

It is common to find basic navigation aids in computer games, including racing car games such as Forza Motorsport, developed by Turn 10 Studios and published by Microsoft Studios; this game can display a path showing optimal position and speed, aiding the user's experience. Disney Infinity, an action–adventure three-dimensional computer game, developed by Avalanche Software and published by Disney Interactive Studios, makes use of a directional arrow showing the location of the player's current task (Figure 2.3.5). This arrow points directly to the player's destination, often suggesting



Total Labor Time
41 Mins

Step Labor Time
3 Min

Tools
Wheel Axle Support

Warnings!
Make sure front wheel assembly axle is properly supported before removing.

Step 3 - Remove Wheel Assembly and inspect for damage.

Warning! Make sure front Wheel Assembly Axle is properly supported before removing Wheel Assembly.

Figure 2.3.6
Interactive three-dimensional digital instructions for aircraft brake pad replacement procedure authored within Deep Exploration v5.0 and published to PDF with CATIA v5 CAD Metadata.

a path through a building or other obstacle that may be causing confusion. The arrow is not responsive to the game's environment, and to improve this aiding technique the arrow would need to direct players around obstructions; a similar approach is investigated using AI paths in Sections 3.2 and 3.3.

The automobile and aerospace industries have made the shift from two-dimensional to real-time three-dimensional workflows, including paperless documentation, as shown in Figure 2.3.6. Both of these industries require a spatial understanding of their models, similar to buildings. The difference becomes clear when comparing the level of modelled detail: because vehicles and aircraft are mass-produced items, more time and attention are given to modelling every element as it will be constructed. Buildings, which are bespoke, are typically modelled to a lower level of detail, commonly to a notional representation of the building form. Owing to the physical scale, spatially simple interiors and high level of detail used by the automobile and aerospace industries, I believe fewer moments of whiteout are experienced compared to architectural models. This is starting to change as BIM models increase their level of detail, although they still do not model every individual element and fixing. However, as computational power increases, every single element used in the construction and operation of building may eventually be modelled digitally.

Section Summary

The work described in this section has covered tools of navigation in virtual environments, methods of spatial orientation, location awareness, distance cognition, and an expanded view of digital architectural models outside of architectural industries. Often, the work with virtual environments has been conducted within abstracted environments compared to those of the physical world, and such studies have therefore not been able to mitigate the importance of detail in supporting spatial cognition while navigating. Industries outside of architecture have begun to provide cues for methods of aiding navigation to reduce and recover from moments of whiteout. There is a gap of knowledge in aiding distance estimation inside digital models.

3 Projects

Exploration inside the unknown

This chapter is structured as follows:
3.1 Translation projects
    The interaction between drawing conventions and digital architectural models
3.2 Navigation projects
    Spatially aware and responsive transitions
3.3 Distance projects
    Scale awareness and supporting distance estimation

The horizon has disappeared, there are no reference points at all. The lighting has become diffused, with no shadows being cast. Within an instant, visibility has gone. Losing all sense of scale and depth perception, unable to distinguish horizontal from vertical. This experience of whiteout is portrayed in Figure 3.0. The following three sections each document a collection of project works. Each section takes the concepts discussed in Chapter 2; spatial cognition, wayfinding, navigation, wayshowing, and pathfinding applying them across the design projects, while critically reflecting on how they reduce moments of whiteout. Allowing easier access to building information, the design projects are evaluated by 'whiteout' criteria of reducing moments of becoming stuck inside the digital model, without the information needed to understand your spatial situation.

Figure 3.1
Williams Field #1 by Anne Noble (2002).

3.1 Translation Projects

Projects:
- Section Pavilion
- Layer Pavilion
- Victoria Quarter Building 6
- Pekapeka

Navigation tools:
- WASD walk
- Mouse look
- Model interaction

Research methods:
- Case Study
- Experimentation
- Critical Reflection

Related publications by the author:

Pelosi, A. W. (2007). Architectural hyper-model: Changing architectural construction documentation. In K. Orr, & S. Kaji O'Grady (Eds.), *Proceedings of the 4th International Conference of the Association of Architecture Schools of Australasia* (pp. unpaged-6). University of Technology, Sydney, NSW: UTSePress.

Pelosi, A. W. (2009). Interactive construction documentation. In X. Wang, & N. Gu (Eds.), *CONVR - 9th International Conference on Construction Applications of Virtual Reality* (pp. 149–154). Sydney, NSW: University of Sydney.

Pelosi, A. W. (2010). Obstacles of utilising real-time 3D visualisation in architectural representations and documentation. In B. Dave, A. I. Li, N. Gu, & H. J. Park (Eds.), *New Frontiers: Proceedings of the 15th International Conference on Computer-Aided Architectural Design in Asia (CAADRIA 2010)* (pp. 391–398). Hong Kong: Association for Research in Computer-Aided Architectural Design Research in Asia.

A stack of enormous sheets of paper the size of a small desk sits on the table; they have just been printed and need to be checked. Are the sheets named and numbered correctly? Are the site plan, floor plans, elevations, building sections, details, and specifications all there? The large, hard-to-handle sheets of paper are flipped back and forth to check section and detail markesrs are calling the correct drawing on the correct sheet. The process takes hours, constantly adding to a mental image or cognitive map of the proposed building, understanding the location of rooms, circulation connections between levels, different wall constructions, and finishes. The methods by which we construct a cognitive image are changing, as are the ways by which we produce architectural working drawings. It has become common practice to exchange digital models rather than just collections of massive sheets of paper drawings. The Translation projects investigate translations of two-dimensional drawing conventions into three-dimensional interactive models.

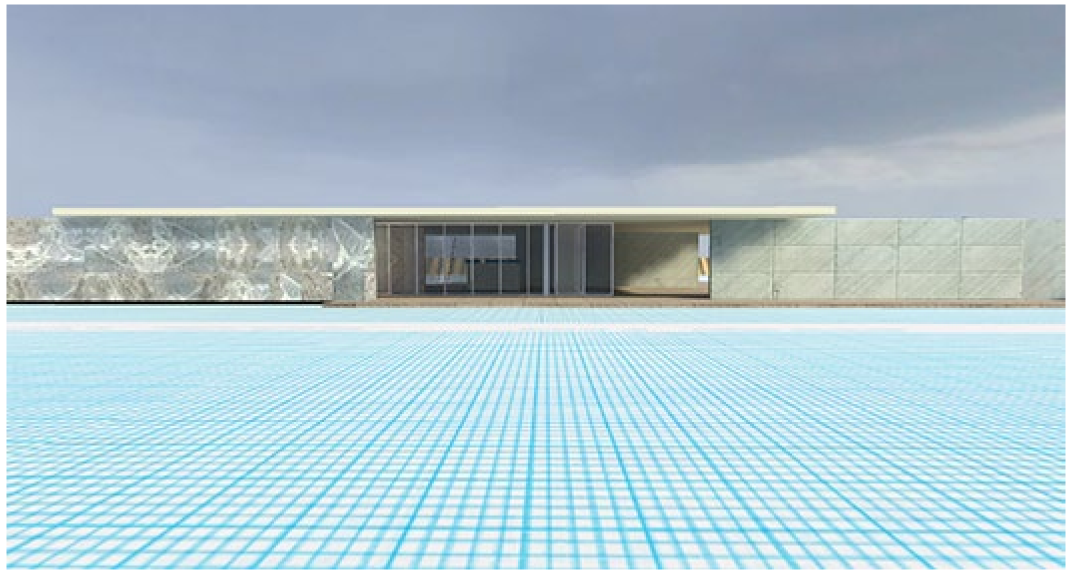


Figure 3.1.1
Section Pavilion (2006) approach to a digital architectural model of Mies van der Rohe's Barcelona Pavilion. It uses graph-paper-textured ground plane, making reference to the translation from two-dimensional drawing.

The 1990s saw the start of the transition from drafting practices of drawing on paper to computer-aided drafting, in which architectural designs are represented as a collection of lines arranged to describe walls, doors, and other elements, producing a very static construct. The term 'BIM' was coined in 1987, but it was more than ten years later that architectural and construction practices started the transition from CAD to smart three-dimensional digital models or BIM models, in which the architectural elements are drawn or modelled as direct digital representations in three dimensions; for example, a wall is modelled 200 mm thick and 2400 mm high at the required length, rather than as two parallel vectors as if drafted by hand. Reports show that the BIM process has an adoption rate of over 70% of architectural design firms in America and Europe (Bernstein, 2014). BIM is still focused on a two-dimensional drawing set as the main output. The BIM industry has recently started to leverage the BIM model beyond the production of two-dimensional drawings. With the transition from hand-drafting to CAD, it took numerous software releases to harness the workflow benefits of referencing external drawings rather than redrawing, automation of title blocks, and drawing standards. It was not only the software that developed; architects and CAD operators also transitioned their own thinking around workflow practices. The projects presented below are explorations into ways of experiencing a BIM model to aid in constructing a cognitive map of architectural designs.

Architectural drawing sets have established rules and methods to enable reading that helps build a person's cognitive map of the proposed building space. Page numbers, section markers, drawing scales, graphic symbols, and dimensioning are all methods that help people navigate through a drawing set. These methods have developed over many years of the manual drafting process, with CAD and BIM software replicating them digitally. Now that architects are creating detailed, complete digital architectural models, how can these drawing conventions be transferred to three-dimensional digital models? The Translation projects are an exploration of architectural drawing conventions within architectural digital models, spanning four projects: the Section Pavilion, the Layer Pavilion, the Victoria Quarter 6 project, and the Pekapeka project.

The Pavilion projects encompass a transformation of the drafting conventions of the section and exploded axonometric within an interactive digital model of the Barcelona Pavilion. Designed by Ludwig Mies van der Rohe, for the 1929 International Exposition in Barcelona, as the German Pavilion, the Barcelona Pavilion was selected as a test because it is often used as an introduction building in learning CAD software on account of its orthogonal geometry and iconic history. Two key experiments were conducted with the Barcelona Pavilion, namely, the Section Pavilion (Figure 3.1.1) and the Layer Pavilion. The Pavilion projects exposed the need for improved navigation methods in BIM models, and showed that two-dimensional drawing conventions may

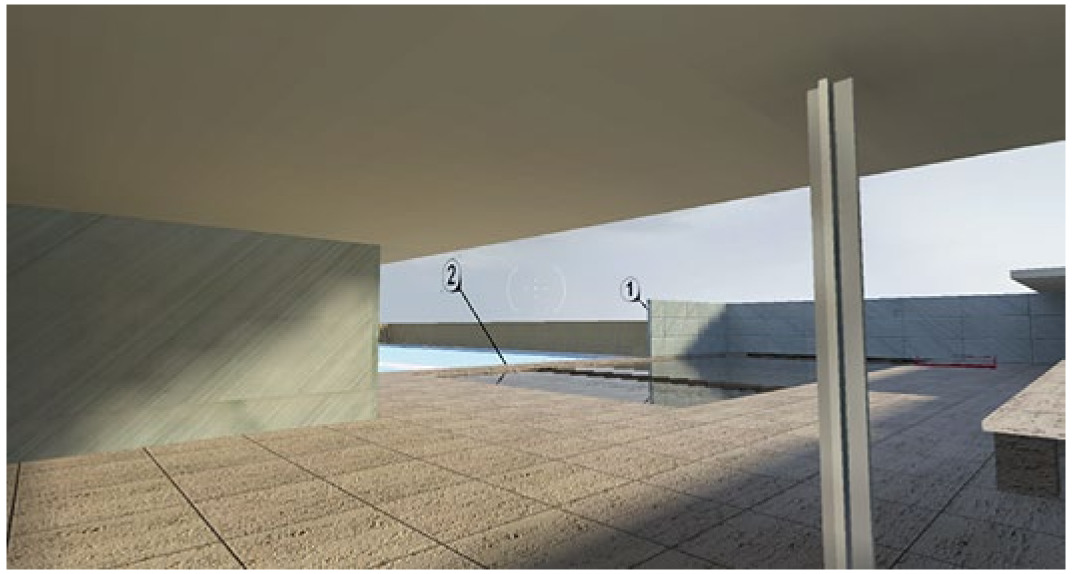


Figure 3.1.2
Section Pavilion (2006) view across the Barcelona Pavilion plinth to section markers (1) and (2).

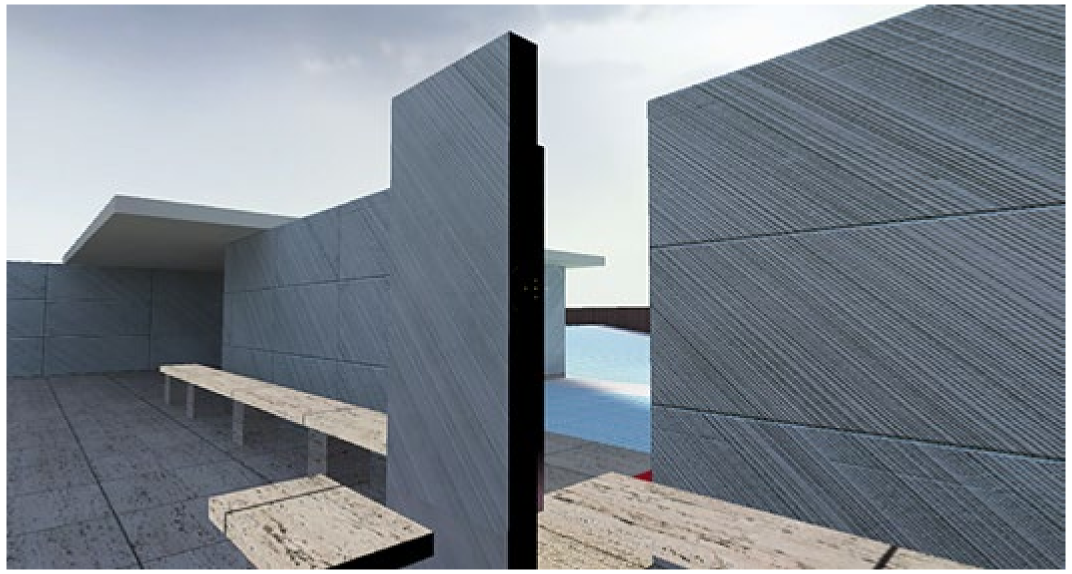


Figure 3.1.3
Section Pavilion (2006) with section (2) activated and in the process of being moved horizontally out from the rest of the model.

not translate productively into digital models. The construction of the digital model affects how we can engage with model geometry: current architectural modelling reflects building form, not the building construction detail and processes required from an architectural specification.

Section Pavilion

Section, one of the primary drawing conventions, was explored as a condition of drawing in an interactive first-person digital architectural model. How could a section be more than its own drawing? How could it be integrated into a model beyond just a slicing of geometry? Digital modelling and reviewing software enables a model to be sliced to view a section cut, hiding geometry and allowing a view inside the model. The section is more than just a drawing: “the section brings to light properties of the composition that would otherwise remain unnoticed upon first consideration” (Guillerme, Vérin, & Sartarelli, 1989, p. 236).

The control of critical information is key for architects for communicating the spatial concepts of a proposed building, the location of drawing views, and the dimensional set-out. BIM allows people to gain access to architectural information in forms other than drawing sets. The way we explore building information continues to develop; the Section Pavilion explores four building sections within a complete model of the Barcelona Pavilion (Figure 3.1.2). All the sections can be activated by clicking on them, extracting an extruded slice the width of a plinth tile grid out from the model to provide an exposed view into the building. Numbered markers identify each section cut, reminiscent of the markers used on construction drawings. Activating one of the thickened sections, the section begins to slide out from the building (Figure 3.1.3), leaving an open slice that can be viewed and comprehended in relation to the building. Once finished with, the section can be slid back into the building.

It became clear that on one level, the animated movement of the sections clearly defined their location within the building, but on another level added confusion about the relationship of the moving elements to the building—is the building going to move? Construction requirements could be misread because the section elements separate components of the building rather than parts of the building. The sectional elements provided a clear contextual relationship to the building while also making the formal building design clouded.

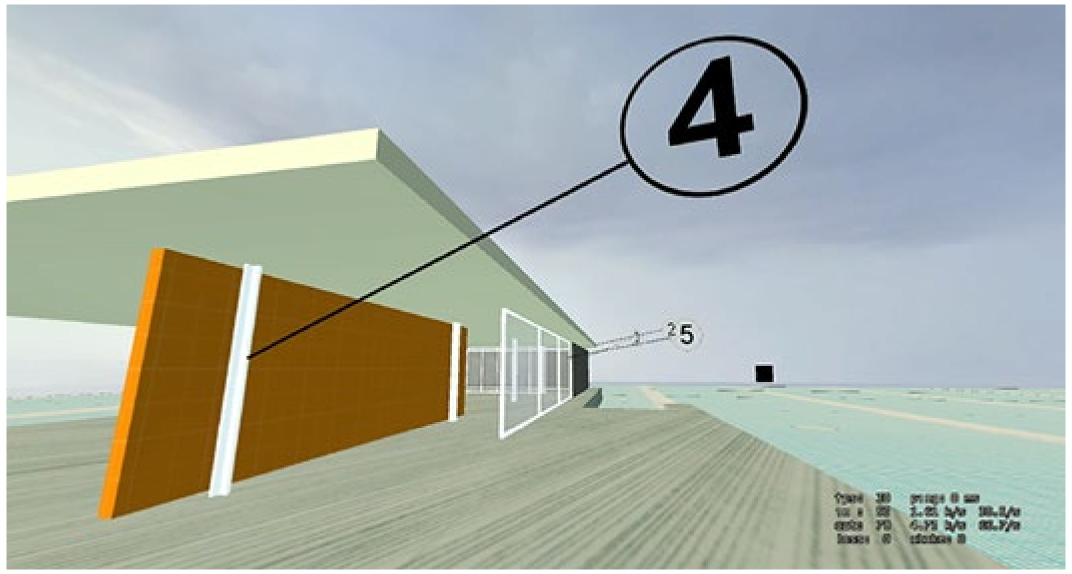


Figure 3.1.4
Layer Pavilion (2006) showing markers that control the vertical movement of each major building element in the Barcelona Pavilion. Marker (4) denotes the cruciform steel columns.

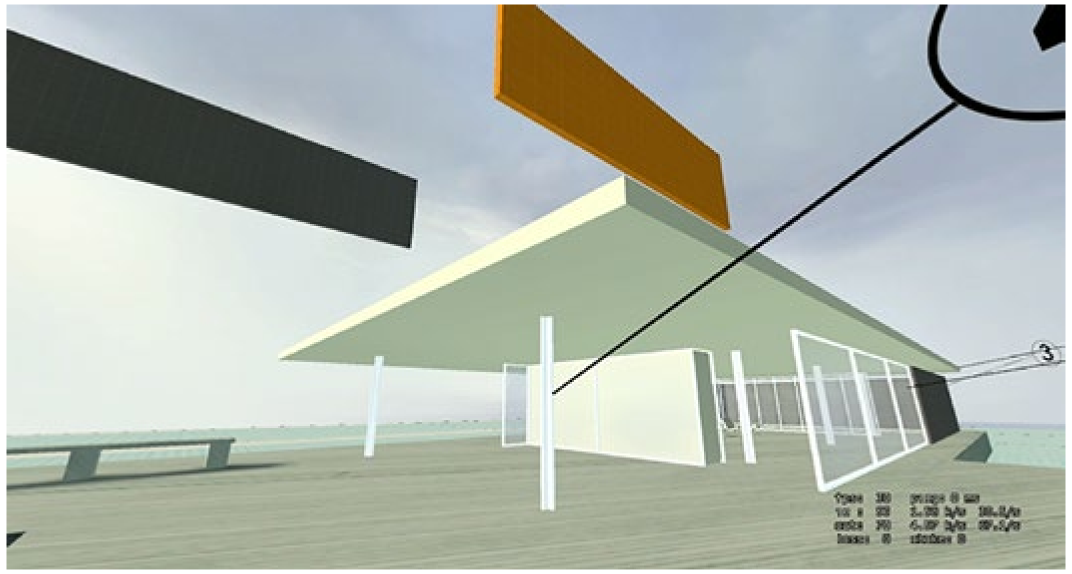


Figure 3.1.5
Layer Pavilion (2006). The Barcelona Pavilion wall moves vertically, as if inside an exploded drawing.

Layer Pavilion

Layer Pavilion is an exploration of an exploded axonometric drawing in an interactive first-person digital architectural model. How can a static drawing become a controllable and dynamic means of accessing architectural information? The Layer Pavilion separates key architectural elements of the Barcelona Pavilion into controllable exploded axonometric; each element has a marker indicating a corresponding keyboard number that actives the movement up from the building platform and then down again (Figures 3.1.4 and 3.1.5). Axonometric and isometric projections allow accurate and measurable three-dimensional drawings to be projected on a two-dimensional surface. Developed in the second half of the sixteenth century, it was not until 300 years later that axonometric became an invaluable tool in resolving complex geometry (Scolari, 2012). According to Ákos Moravánszky (2014), the axonometric is not tied to the observer, thus allowing an objective means of technical drawing. With the adoption of architectural digital modelling, the requirement of parallel projection is changing, and it is no longer a required architectural skill. Axonometric drawing was a technique of its time that has a legacy connection to the digital and which enables the viewing of digital models projected in parallel. The layer project investigates an interactive first-person perspective of the exploded axonometric drawing.

Both the Section Pavilion and Layer Pavilion utilised the computer game engine Source SDK developed by Valve Corporation, a software development kit (SDK) that enables modifications to be made to Source engine. Different digital models of the Barcelona Pavilion were created for the section and layer projects in SketchUp as individual elements and translated for authoring in Valve Hammer Editor. Hammer is a game-level editor that allows ‘game’ levels to be created. The rendering, collision physics, and interactions were created and compiled within Hammer. Source SDK is proprietary software that is available for free download for non-commercial use, making interaction and rendering impossible within BIM software. However, because of its computer-gaming focus, the powerful engine Source SDK has many limitations, and workarounds were required to accomplish the Pavilion project. Source SDK is optimised for computer gaming with no consideration for other types of interaction, and therefore functions that are common in CAD and BIM software required complex solutions.

Navigation aids in the Translation projects include a rendered cloudy sky and a solid ground plane that act as landmarks or reference datums. Digital architectural models typically are floating in digital space with little or no reference to up or down, although Autodesk proposed a solution with ViewCube (Khan et al., 2008). With ViewCube, the viewer has a direct visual understanding of vertical orientation. Often, the orbit tool will have built-in limits to keep the model vertically aligned; however there is usually no representation of vertical orientation with orbit tools.

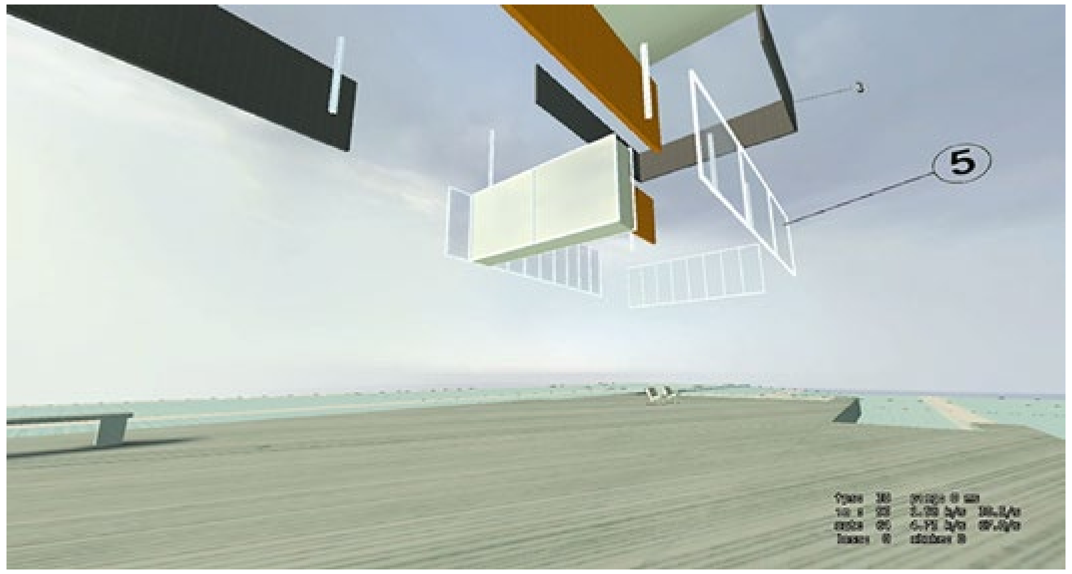


Figure 3.1.6
Layer Pavilion (2006). The Barcelona Pavilion is exploded vertically, with each building element controlled by the viewer.

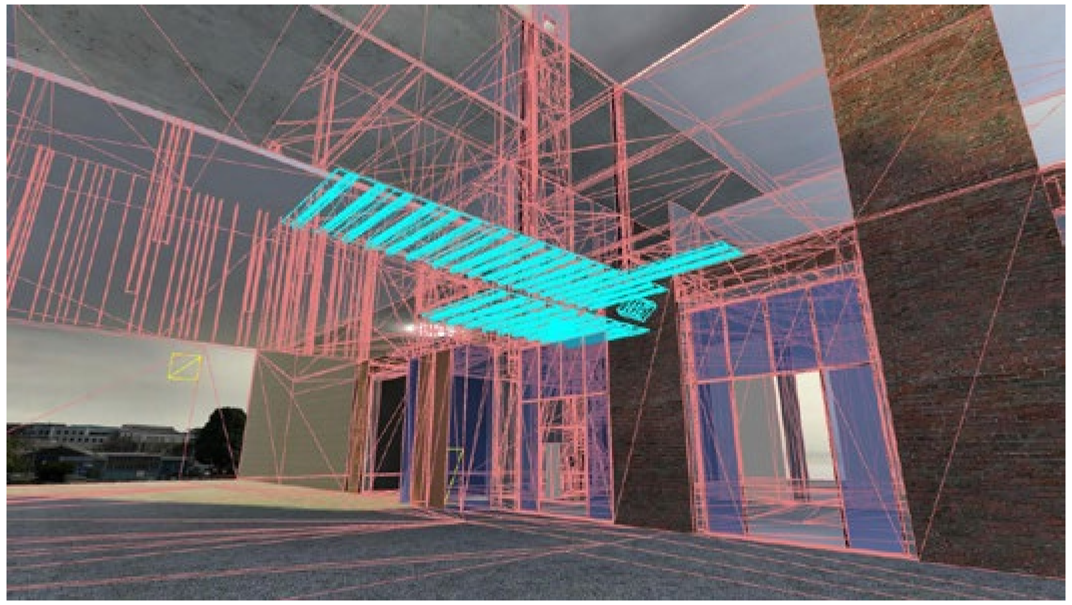


Figure 3.1.7
Victoria Quarter Building 6 (2007). Testing the visual control of building elements in Source SDK engine. Project in collaboration with Architecture Workshop.

The Pavilion projects created more questions than answers. The Section project explored the concept of integrating the section into the building model, becoming its own geometry based on the architectural design of the pavilion. More than a just another drawing, it became part of the architecture. The Layer project made a controllable exploded axonometric of key architectural elements (Figure 3.1.6). Both of the projects highlighted issues of comprehension and model navigation, including technical issues resulting in workarounds or not being able to test ideas, which greatly limited both projects.

Building projects

The Translation projects initiated the exploration of working with an architectural practice on a live project, creating interactive digital architectural models to aid in spatial cognition. Two different project types were tested with two different architectural practices. These projects set out to investigate a translation of the three-dimensional digital models that the practices used in the design process to an interactive real-time first-person digital environment. The first of these explorations was a multilevel, mixed-use commercial development by Architecture Workshop, and the second was a small family holiday home designed by the architecture firm Custance.

Victoria Quarter Building 6, sited in Auckland, was a proposed mixed-use redevelopment designed by Architecture Workshop. It is a meeting place for living, working, and recreation. The proposal included a lower level of retail, hospitality, and three levels of double-storey apartments above a laneway. I began exploring the project during the preliminary design phase; the bulk of the building had been drawn as a three-dimensional model in ArchiCAD (architectural BIM CAD software). To improve the quality of real-time rendering and interaction, I decided to continue to use the Source SDK game engine, as in the Pavilion projects.

It was not possible to import the model geometry directly into the game engine. The geometry needed to be optimised to run effectively or be remodelled. Because of possible model deformations, a new model was created. World editor Hammer is only capable of operating in Imperial units, with one hammer unit equalling approximately 3/4 inch. This is based on 16 map units being equal to one foot (Vavle Developer Community, 2007), so metric measurements are difficult to translate. The game space is not directly analogous to real space. The unit size is defined to allow processor efficacy using a base-2 system. This created model accuracy conflicts between the ArchiCAD model and the Hammer model, causing interoperability issues, as I was not able to create accurate interactive models that followed the required timelines.

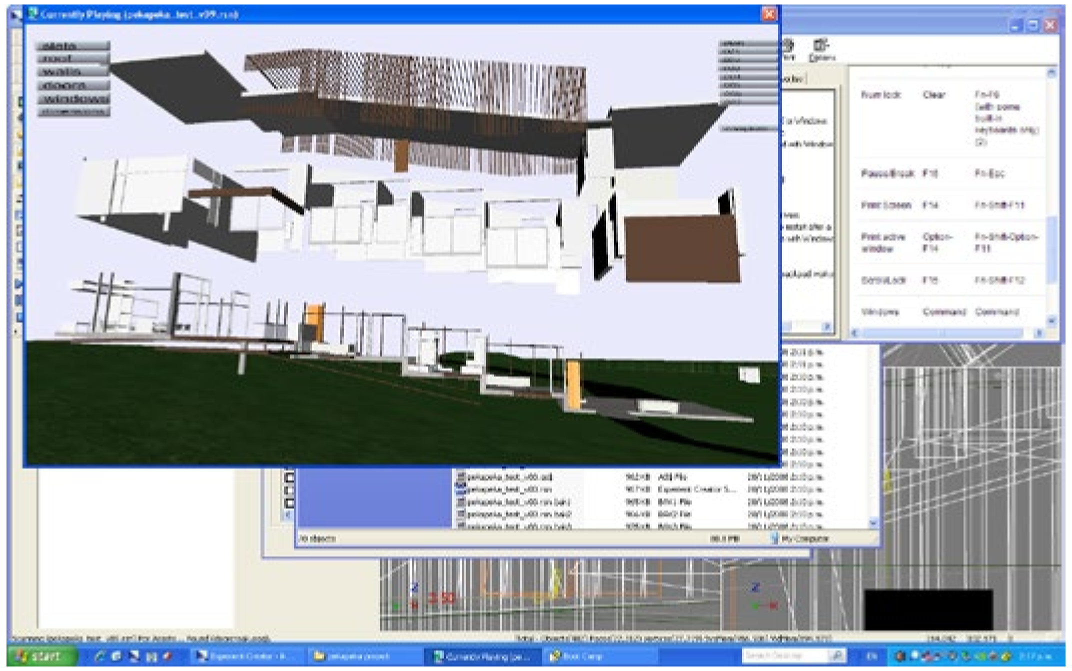


Figure 3.1.8
Pekapeka project (2008), in the Esperient Creator authoring environment.
Project in collaboration with Custance Design.

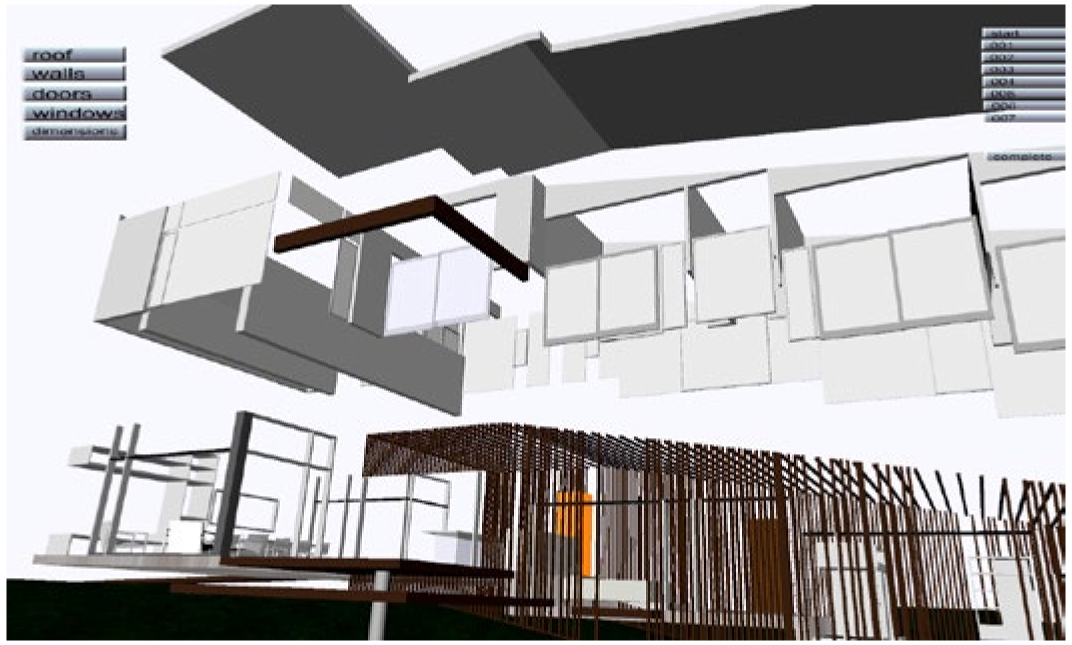


Figure 3.1.9
Pekapeka project (2008), showing user controllable model geometry.
Because of processing and optimisation limitations, the project was not able to run smoothly.

Source engine provided interactive controls that were not available in BIM software. The ability to have the physics engine support avatar geometry collision allows an interactive first-person walkthrough of the building. This was used to test the spatial qualities of a vertical sliding four-square-metre translucent second window and to try to inform the construction process (Figure 3.1.7).

In an effort to address the issues that surfaced in the Pavilion projects and in Victoria Quarter Building 6, a new software, Esperient Creator, was tested on a smaller domestic-scale project. Pekapeka bach (a traditional beach holiday home) (Figure 3.1.8) was the result of a small-design competition won by Katya Gibb of Custance Design. Esperient Creator originally started as a standalone game-authoring tool that was developed into a three-dimensional interactive media platform by Right Hemisphere. Esperient Creator was integrated with Deep Exploration CAD, highly interoperable software capable of translating numerous three-dimensional file formats. Again, I started involvement with the architects during the preliminary design phase, in which Custance had a detailed model created in Revit. The house is designed to follow the natural contours of the land, rising onto a small dune where the main living space looks out to a view of Kapiti Island, wrapped with a delicate timber-slat sunshade. The premise of the project was to further test the explodable model and to connect building specifications directly within the digital architectural model (Figure 3.1.9). A controllable display of dimensions was also tested.

In the process of translating the BIM model from Revit to Esperient Creator, the geometry either became corrupted (Figure 3.1.10) or resulted in high polygon counts that slowed Esperient Creator's rendering engine to inoperable frame rates. The major cause of excessive polygon count was this inclusion of imported objects from Revit, including furniture, whiteware, and bathware (Figure 3.1.11). These items could be easily removed, rectifying the processing problem. The removal of these items impacted the readability of the scale of the space. The windows, doors, and timber slats needed to be redrawn to help reduce polygons further to allow correct rendering. The model was then divided into major building elements to animate with vertical movement in order to create an interactive separation or explored perspective. It quickly became evident that the model had been constructed as a finished form, with little or no consideration to construction detailing. Detailing had been considered in the design process but was represented as two-dimensional working drawings. This limited the workflow between the Revit model and the real-time three-dimensional exploration, and any changes in the design needed to be optimised for interaction in Esperient Creator. The landscape was another polygon-rich critical element that directly influenced the performance of the software.

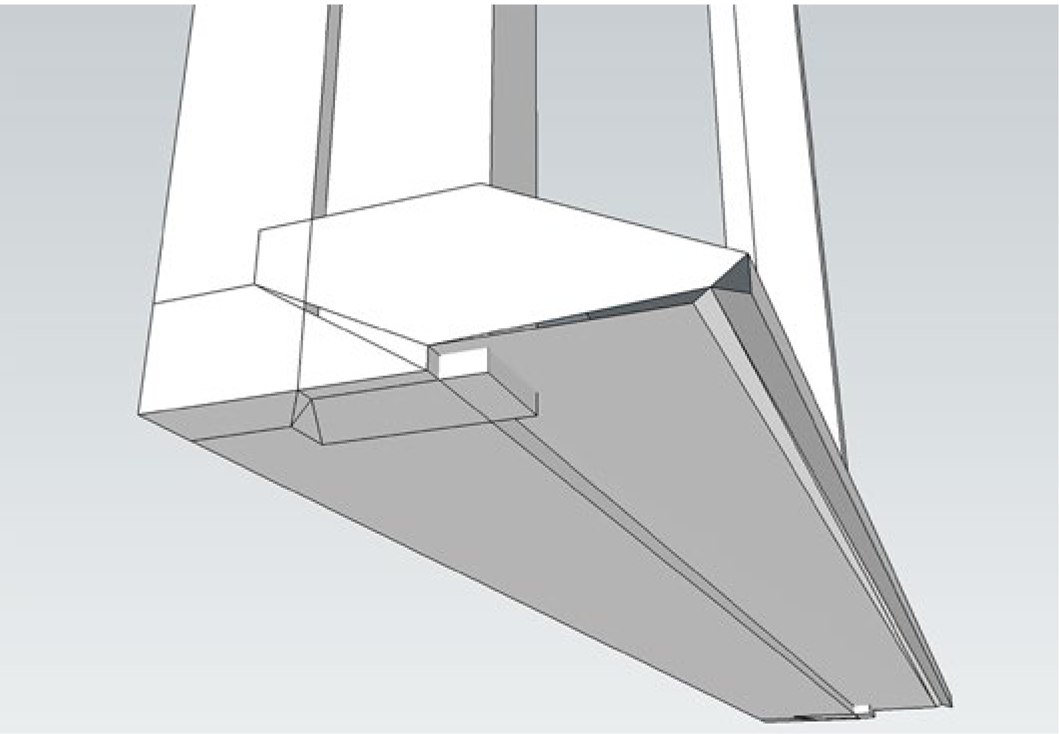


Figure 3.1.10
Detail of corrupted geometry after translation from Revit, which added polygons and increased the processing requirements of the model.

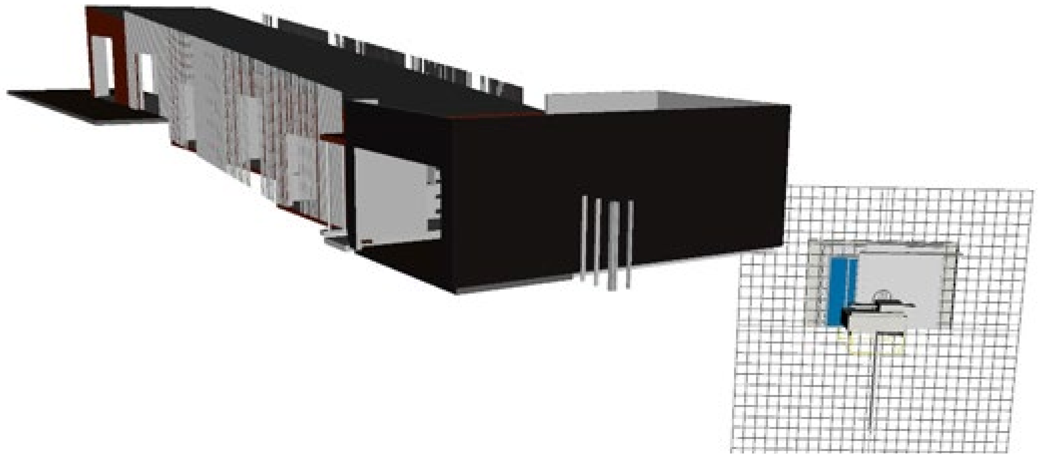


Figure 3.1.11
Interoperability conflicts after importing the Revit model in Esperient Creator to author real-time interactivity. Some model elements were centred at the origin of the software whereas others were located relative to the building's location.

Once all the model geometry issues had been addressed, the interaction enabled a clear understanding to be gained of the subtle shifts in floor levels, of the spatial location of rooms all on different levels, and of the relationship of the timber-slat sunscreen that wrapped the bedrooms. Nodes were added at key architectural points that could be clicked on to display critical dimensions. In principle, this worked well to enable design control of measurements within the digital model. BIM review software provides restricted access to dimension tools.

The project was abandoned because of client and architect delays, technical issues, and limitations of the software. However, the building was built and enjoyed by the owners. I refer to Victoria Quarter Building 6 and the Pekapeka as productive research projects because they revealed the difficulties of interoperability, of limitations of the software, and of spatial cognition inside digital architectural models.

Section Summary

The Pavilion projects set the baseline for my doctoral research. In this exploration of interacting with BIM models, a number of challenges emerged. The challenges that helped inform the research can be categorised into two main areas, namely, interaction and geometry. These two areas are interconnected: the level of complexity of the geometry directly relates to the methods of interaction required to access the spatial information, often causing problematic whiteout moments. A review of the literature and practice identified an increasing level of complexity of information in architectural documentation (Bisharat, 2004; Eastman et al., 2011; Gao, Walters, Jaselskis, & Wipf, 2006; Price, 2010; Simpson & Atkins, 2005; Tilley et al., 1997). As buildings have increased in complexity, so has the amount of information required to build them, from verbal instructions with a relatively small number of drawings to now including up to six-dimensional architectural digital models (adding scheduling – 4D, cost – 5D, and facilities management – 6D to the three-dimensional model) with hundreds of pages of drawing and specifications.

The way in which we access and interact with architectural information has also changed, usually forced by the increase in the complexity of building requirements. In addition, the way in which we navigate an architectural drawing set has developed with the increased number of drawings. From one sheet to many came markers and tags that reference different drawings at another scale on other sheets. With the digitisation of architectural drafting came an increase in the number of drawings, which could be attributed to the relative ease of creating drawings and the increased use and complexity of building systems. With the expanding use of BIM there has been a corresponding expansion of information that requires different ways of navigation. The Translation projects exposed the need to investigate how we can access and comprehend this increase in data.

To enable explorations of navigation to extend beyond what was currently provided by BIM review software, other platforms were tested. To continue investment of time into A-grade computer games, companies realised that by opening up access to level editing software, the sophisticated game engine could be leveraged by the masses to give longevity to the technology (Andreoli et al., 2005). When the Translation projects began in 2006, two key three-dimensional computer game engines made possible the manipulation of geometry required: Unreal engine developed by Epic Games and Source game engine developed by Valve Corporation. Both allow custom geometry and textures to be imported into an editor where interaction and environmental elements are added. Because of a consistently scaled workflow, rendering, and interactive capabilities, Source game engine was selected and used. Source provided many features, such as the ability to logically control and trigger geometry movement in real time, which provided a first-person game navigation control that did not readily exist in BIM reviewing software at that time to be investigated. Some first-person navigation control has been introduced to many BIM softwares, with varying levels of execution. Owing to the computer gaming focus of Source engine, only limited types of interaction could be accessed. The engine also had limited publishing and deployment constraints, restrictive file sizes, and advanced processing and graphic power requirements. Source engine required constant updates that drastically changed how the software could operate, frequently causing complete reworks of the projects. In response to the limitations tested across three projects of varying complexity and scale, and with the constant problems and frustrations of Source engine, another software was tested with the Pekapeka project, Esperient Creator. This software offered the flexibility to control and programme a large range of interaction and geometry well beyond that provided by Source game engine. Esperient Creator was able to publish and deploy manageable self-contained packages that Source game engine was not. However, interoperability with Revit was still a major issue, regarding not only geometry optimisation but also other data translations and connections with design phases due to reprogramming interaction and animation of the model.

Interoperability is an ongoing problem (Beall, Walsh, & Shephard, 2003). The process of translation from CAD and BIM software to a real-time three-dimensional computer game engine may work smoothly in theory, but in practice can cause major problems when converting the model data to a format that can run efficiently in real-time three-dimensional software. Unexpected results are common in the translation process and cause major difficulties when imported into a real-time digital environment. Optimising geometry becomes a constant problem for a smooth workflow. This can be attributed to the typical method CAD and BIM software packages used to display model geometry, that of boundary representation (or B-rep). A valid B-rep model is defined by a combination of geometry (shape), topology (how things are connected), and tolerances (how closely do they actually fit together). Typically, real-time three-dimensional software requires a triangulated polygon mesh. Objects created and sorted as polygon meshes are constructed of vertices, edges, faces, three- and four-sided polygons, and surfaces. However, many game render engines support only three-sided faces or polygons. In the triangulation process, the number of polygons can dramatically increase, thereby decreasing the frame-rate and producing slow, unresponsive navigation. In some situations, model geometry can be relocated incorrectly. Figure 3.1.10 shows examples of geometry triangulation of a door frame and model components relocated within a Revit Architecture model translated for use in a game engine (Pelosi, 2010).

In this section, the Translation projects investigated methods of interacting with building geometry and data, and demonstrated the need to allow people improved access to expanding amounts of spatial building information. The Section and Layer Pavilions explored the translation of drawing conventions into interactive models restricted to the first-person perspective. This revealed potential new methods of interaction with building information, allowing more accessible information. The projects exposed limitations of workflow and interoperability between BIM software and game engine software To explore this potential of interaction and the limitations of software, the Victoria Quarter building 6 and Pekapeka projects, which were aligned with architectural practices on live projects, proved that the limitations were problematic for the interaction of model geometry and navigation of digital architectural models. Limitations of workflow and interoperability were tested across two software platforms, Source engine and Esperient Creator, and across the four projects. These problems have been solved or are being worked on by others within the building industry and beyond, so were considered outside the further scope of the present research study. The Translation projects revealed the difficulty of navigation and spatial cognition inside information-rich digital architectural models.

Figure 3.2
Antarctica: The Grain of White #15 by Anne Noble (2009).

3.2 Navigation Projects

Projects:
- Pointer
- Pathfinder
- Space Trace
- Show Me

Navigation tools:
- WASD walk
- Point to walk
- Mouse look
- AI pathfinding
- Guided path
- Automatic path transition
- Breadcrumbs
- Metadata display

Research methods:
- Case study
- Observation
- Questionnaire
- Experimentation
- Critical Reflection

Technical assistance:
- Oliver Blair

Related publications by the author:

Pelosi, A. W. (2013). Model Command – Spatial Comprehension of 3D Digital Environments. Open Systems: *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia* (CAADRIA 2013). Singapore 15–18 May 2013, pp. 417–426.

Pelosi, A. W., Blair, O. (2011) *Space Trace*. Spatial projection installation, 10 m × 10 m × 4 m. Included in Wellington Lux, Massey University, Wellington, New Zealand (8–10 July).

We navigate every day, through familiar territory, and for some people this can include digital models. Often, those involved in the design process have a cognitive map that has developed alongside the design, from the first sketch, to the site visit, to the review of working drawings. People that have not been involved in the design process have not had the same time to develop a cognitive map as rich as that of the designers, as if in an approaching whiteout, as shown in Figure 3.2. However, those not involved in the design are required to rapidly develop a comprehensive cognitive map of a proposed building, often in different ways to that of the designers. In which ways can a digital architectural model be viewed to aid someone reviewing a building proposal?

In this section, the second collection of design projects explores methods of providing assisted navigation through the interiors of digital architectural models. Four projects were developed to investigate innovative methods to improve spatial cognition through wayfinding.

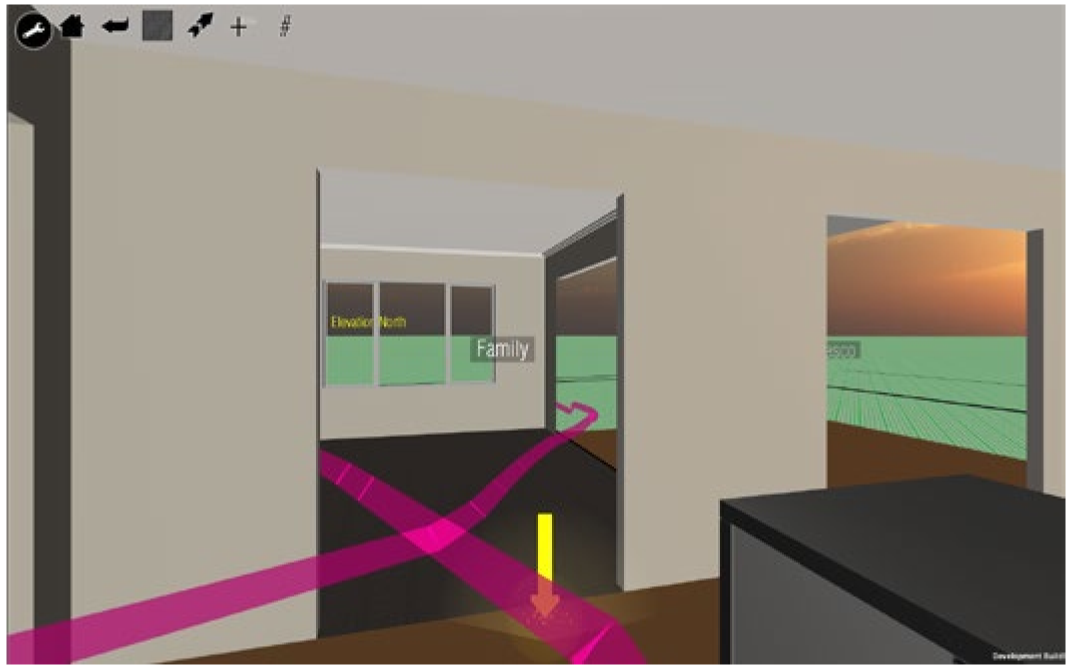


Figure 3.2.1
In Pointer (2011), a yellow arrow points to a destination to which users can be moved by clicking on the arrow. A trace of the path travelled is displayed as a magenta trail, helping to orient the user inside the digital architectural model.

"A navigator needs to understand spatial relationships among objects in virtual environments to construct a comprehensive cognitive map. Being able to explore the space is as important as being able to reach the destination quickly" (Wu et al., 2009, p. 3). The Navigation projects are an investigation into methods of aiding navigation beyond the common navigation tools of pan, zoom, orbit, walk, fly, and look. Navigation tools are an important collection of methods that enable people to access any part of a model; however, they can be awkward to move around, as they allow only a single function at a time. Within the last five years, select BIM software packages have introduced a 'game' mode that enables walking and looking at the same time, improving the mobility to explore in first-person or third-person perspective, a tool that was not common at the start of my doctoral candidature. However, there are still times when people become lost inside a building model. The Navigation projects explore other methods of navigation interaction, across four investigations: the Pointer project, the Pathfinder project, Space Trace, and Show Me.

In response to the software limitations faced in the Translation projects, Unity game engine (developed by Unity Technologies) was used for the Navigation projects. I selected Unity as a cross-platform game engine with an integrated development environment that is able to publish to desktop platforms, the Web, and mobile devices. A smooth workflow for importing model geometry is supported, resulting in direct import of building models with only minor optimisation required. Unity includes an A* pathfinding plugin that automatically generates a navigation mesh or navmesh. A navmesh is a data structure used to define accessible space used in AI pathfinding applications. With the incorporation of a navmesh, pathfinding can be responsive for the interior layout of a building.

Pointer

The Pointer project encompasses several navigation systems covered in Chapter 2, including the availability of a small view-in-view location map, breadcrumb trail, room labels, and predefined locations, and a click-to-walk movement option. A two-storey, four-bedroom family home is used to explore these navigation aids inside a building context. The view-in-view location map has been shown to aid in improving both spatial orientation and location awareness (Wu et al., 2009). The breadcrumb trail has been discussed by Rudy Darken (1993) in the context of virtual reality studies; although useful, such trails can become confusing if left, and there has been fairly limited discussion of its use in architectural practice. A magenta trail that fades after 60 seconds traces the path travelled (Figure 3.2.1). The trail provides a drawn representation of the path travelled by the viewer, indicating the areas of the building that have been travelled, clearly informing the views and movements and helping to build a cognitive map of the model. This project revealed

Figure 3.2.2
Pointer (2011) makes use of a magenta trail of path travelled, a yellow pointer, predefined views, and view-in-view location map in the lower-left-hand corner, all of which help to orient the viewer.

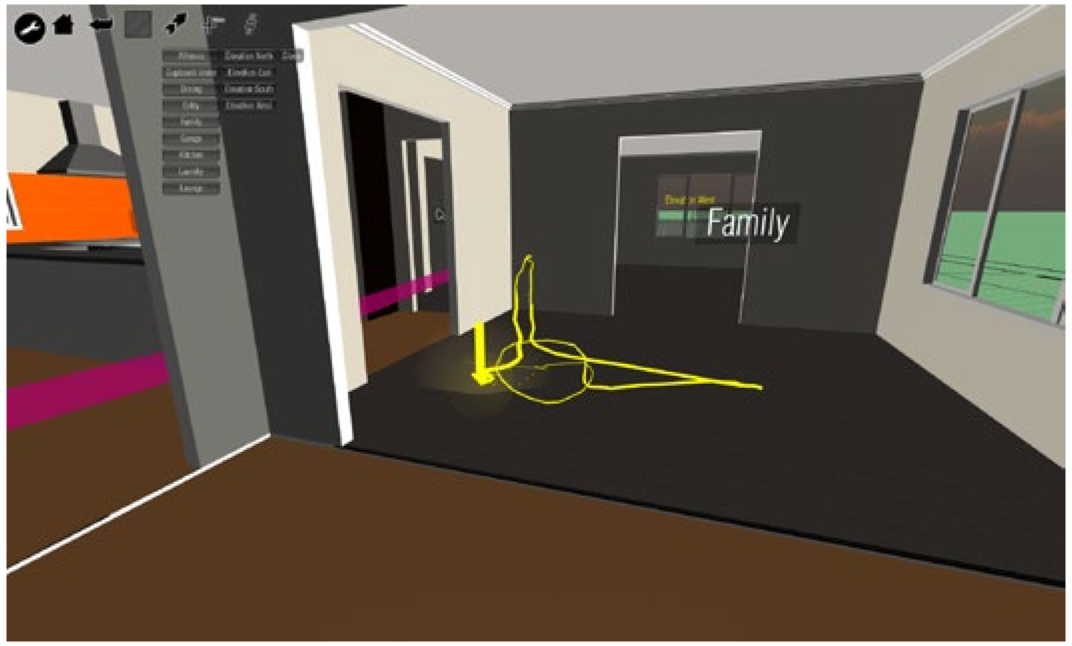


Figure 3.2.3
Pointer's (2011) yellow arrow leaves a temporary yellow trail of the mouse movements, allowing the user to distinguish an area.

improvements in spatial cognition by providing user location with room labels and in-view map, identification of travelled path with breadcrumb trail. Challenges in developing methods of travelling within digital models became apparent as whiteout conditions still occurred.

The Pointer project gives another means of moving inside the model, and is derived from the iOS first-person technology demonstration, Epic Citadel, developed by Epic Games with Unreal Engine 3. The demonstration allows people to navigate through a fictional medieval village by touching the screen at the location to which they want to move; an arrow is placed at the touched location, indicating a new destination to which the user is then walked. The ease of this navigation technique inspired the yellow pointer in the Pointer project (Figure 3.2.2). The pointer is a marker that draws a yellow trail of the path of the mouse; the yellow trail illustrates the path that the mouse has been dragged over, and disappears after three seconds. It acts as an indicator of the location to which travel is desired.

A key method of moving between spaces is with predefined views; this is provided in the Pointer project with a drop-down menu, as shown in Figures 3.2.2 and 3.2.3. Historically, this has been achieved by direct hyperlinking between set camera views, allowing rapid movement to occur between known spaces. However, no location, orientation, or distance knowledge is conveyed in the process of instantaneously hyperlinking, often inducing moments of whiteout. It is now common for a spatial transition to occur between the predefined views. These transitions animate the camera movement, providing an understanding of difference in location, orientation, and distance between views. These transitions work well for exterior views around a building. However, when navigating inside a digital architectural model, the transitions do not respect the model's building geometry, flying through walls and floors and taking a direct path to the new camera location, often causing moments of whiteout.

By providing intuitive navigation tools, the pointer enables a person to easily traverse a complex digital architectural model. There are still moments when the user can become stuck or lost if using only the pointer to navigate. The tool is a point-and-click means of moving through a digital model. Further development of the pointer could extend the work of Autodesk Research's HoverCam (Khan et al., 2005). With an interactive three-dimensional navigation tool for proximal object inspection, that included proximity limits for the camera, it becomes much harder to become stuck or lost against model geometry.

The project included the ability to undo the last navigation move and a 'home' command that returns the user back to the starting point. These options are available in most BIM review software but are not typical in gaming

Figure 3.2.4
Pathfinder (2011), an interior perspective during an AI transition through the building model, following a yellow and automatically generated pathway, leaving a thin blue trail.

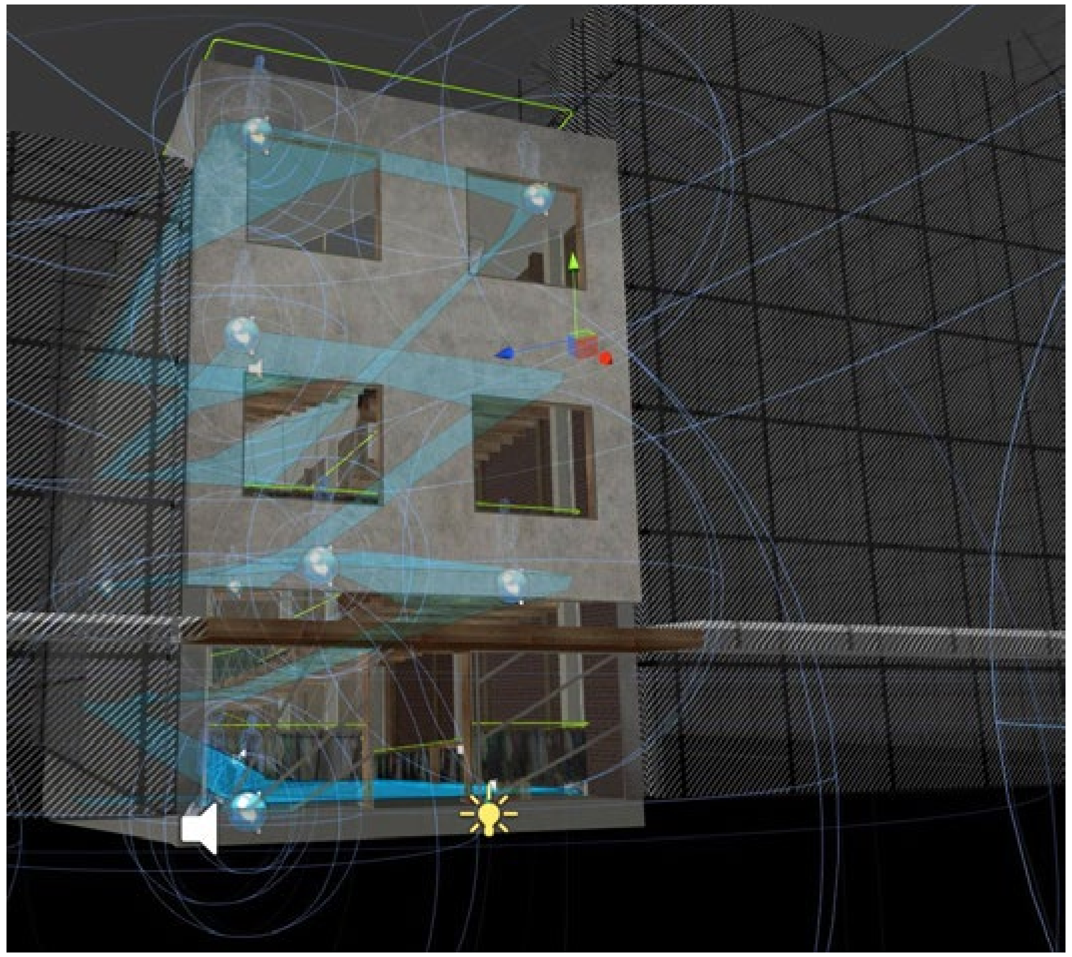


Figure 3.2.5
Pathfinder (2011) investigates AI pathfinding using a navigation mesh and sound volumes (speaker icons with spheres representing volume) to denote different spaces within a digital architectural model.

environments, and it is important to understand how they can be used and if they help. It was clear that although people may not know of these tools, they are useful for regaining situational awareness or for correcting that moment after becoming stuck or confused. Although these tools are useful, they do not reduce moments of whiteout, only helping in their recovery.

The Pointer project explored ways of navigating through a digital architectural model by assisting navigation by providing a click-to-walk or pointer tool that directs the user to the desired visible locations. The predefined views proved problematic in this case, as they did not provide clear spatial transitions between views. The succeeding project, Pathfinder, investigates possible solutions to ensuring spatial cognition while inside a digital building model.

Pathfinder

Building on the explorations undertaken in the Pointer project, responding to both its strengths and weakness, the Pathfinder project investigates extending the transitions between predefined views (for which it creates spatially responsive transitions). It includes a review of software titles including, amongst others, Navisworks, Sketchup, and Solibri. However, the transitions ignored building geometry, often cutting straight through walls, missing the opportunity to express the correct spatial quality. The Pathfinder project introduces spatial transitions that are spatially responsive, shown by the thin yellow line in Figure 3.2.4, utilising AI pathfinding algorithms between present locations in the building, including plan and section cuts.

Pathfinding strategies are typically core to any AI computer gaming movement system and are developed to realistically control agent movement from one location to another in a game world (Graham et al., 2003). There are many different strategies for achieving realistic pathfinding systems, which can be categorised into two main approaches: undirected and directed. An undirected approach is a basic trial-and-error method that would not be useful for finding the best path alone. A directed approach tests possible paths that assess, in this case, the shortest distance or most advantageous route to a destination. Directed pathfinding algorithms are most commonly used in computer games.

In conjunction with AI pathfinding, the project employed three-dimensional location-based soundscapes to provide audible differentiation between interior and exterior, as shown in Figure 3.2.5. In this case, they are basic soundtracks that give a sense of difference between interior and exterior. The soundtracks are related to the spaces only in an abstract sense, with urban street noises for the exterior and a song for the interior with a crossover of the sounds at the interface between zones, providing a non-visual cue to aid location recognition. Although the soundscapes increased basic location

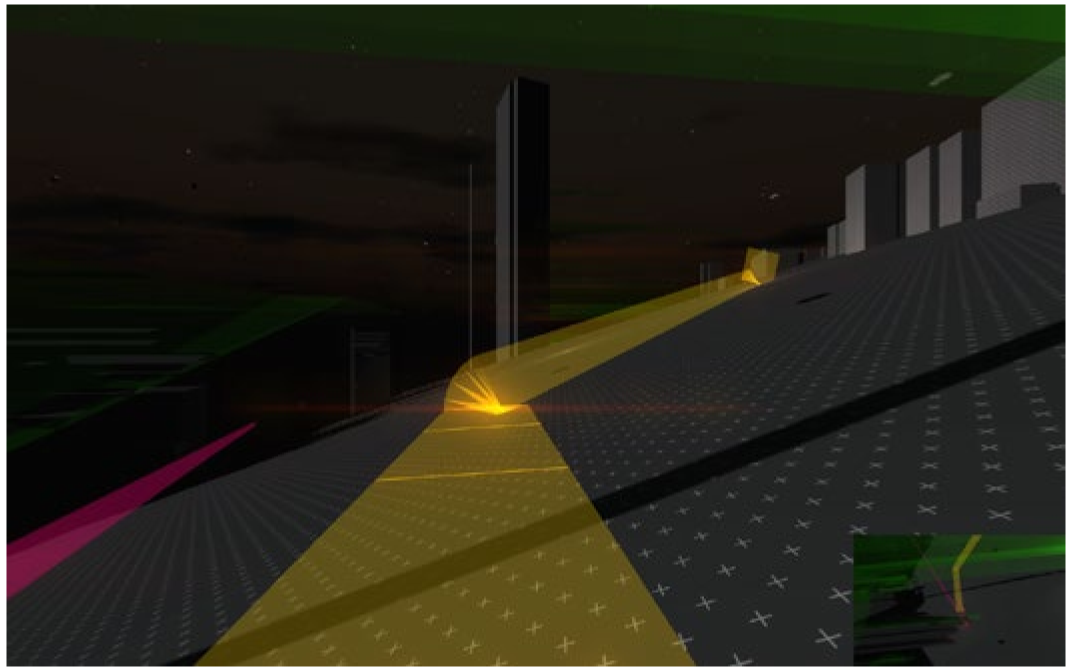


Figure 3.2.6
Space Trace (2011) sensors the room and on the detection of movement activates automated navigation within the digital model, highlighting pathways in yellow of the direction in which the viewer will be moved.

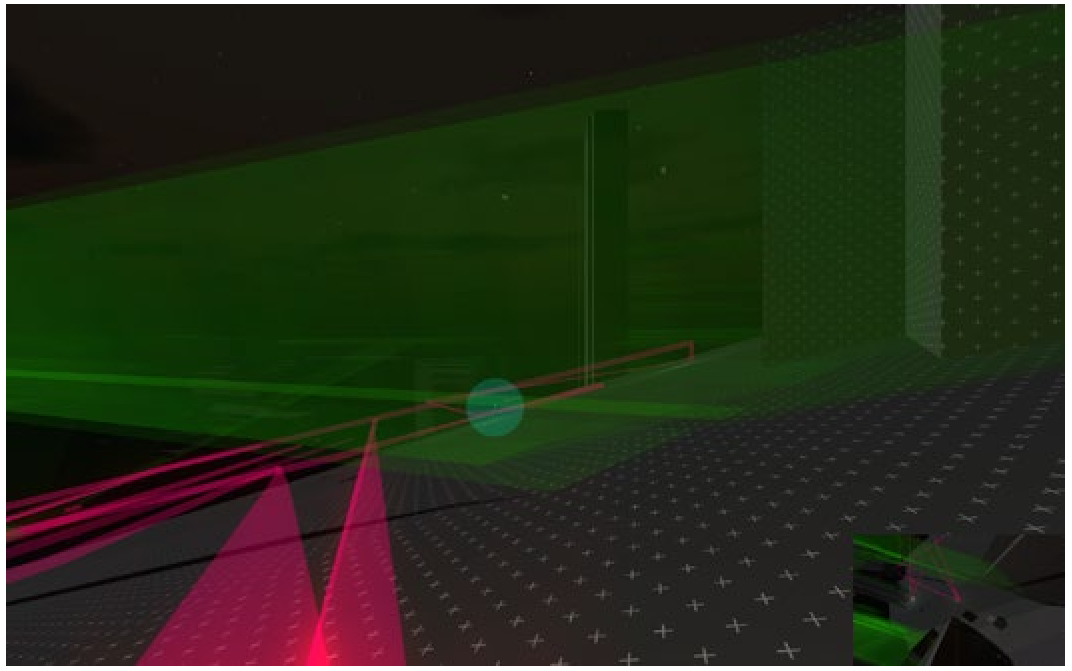


Figure 3.2.7
Space Trace (2011). Magenta trails trace the paths that users have travelled using AI pathfinding, recording a history of their navigation.

awareness, two key conditions needed to be met. First, the device being used to experience the digital architectural model requires at least one active speaker. Second, appropriate soundscapes are needed for each distinct space, beyond interior and exterior, as a viewer could foreseeably stay within one of these zones, unaware of differences between spaces. The computer games industry utilises reverberation zones that distort sound according to described qualities, helping to differentiate between spaces or rooms. For this technique to work, a sound source is required: footsteps, breathing, gun-fire, and vehicles are commonly used in computer games. The only sound that makes sense to use in the architectural fields is footsteps; however, this is only useful when a model is being experienced from a first-person or third-person view. It has been shown that auditory cues help navigation (Lokki & Grohn, 2005). The simulation of acoustic properties for virtual environments is a well-documented research area (Naef, Staadt, & Gross, 2002) and one that has provided successful examples of improving navigation and spatial cognition, such as the implementation used for computer games. After exploration, this was considered outside the scope of the present research study.

AI pathfinding was used to explore walkable routes within the building model, enabling an automated path to be created that calculates the shortest distance that can be traversed. Unity game engine uses a version of the search algorithm A* for pathfinding. The following project, Space Trace, investigates motion sensing as a method of input for active navigation of an abstract digital model with AI pathfinding enabled to generate new pathways in real time.

Space Trace

This project, ‘Space Trace: Navigating Digital Space’, explores abstract methods of navigation input for experiencing three-dimensional digital space. The project explores a range of navigation and orientation systems to help spatial comprehension via reactive methods of navigation. Commercial computer game engines often allow a first-person or third-person view that provides a consistently scaled view of a digital space that is navigated by walking or flying. This mode of navigation provides the viewer with a stronger understanding of scale and of relationships within a proposed building than do standard modal navigation tools. It is possible, however, to become stuck in corners if one attempts to move through solid geometry. Space Trace investigates methods of navigation by leaving the typical controls of keyboard and mouse for motion sensing. The navigation relies on the AI pathfinding utilised in the Pathfinder project, using motion to trigger movement between set locations inside a digital model. Trails of colour light the path between different locations, shown in Figure 3.2.6 as a yellow line. Trails of breadcrumbs are left, tracing the movement through the model (Figures

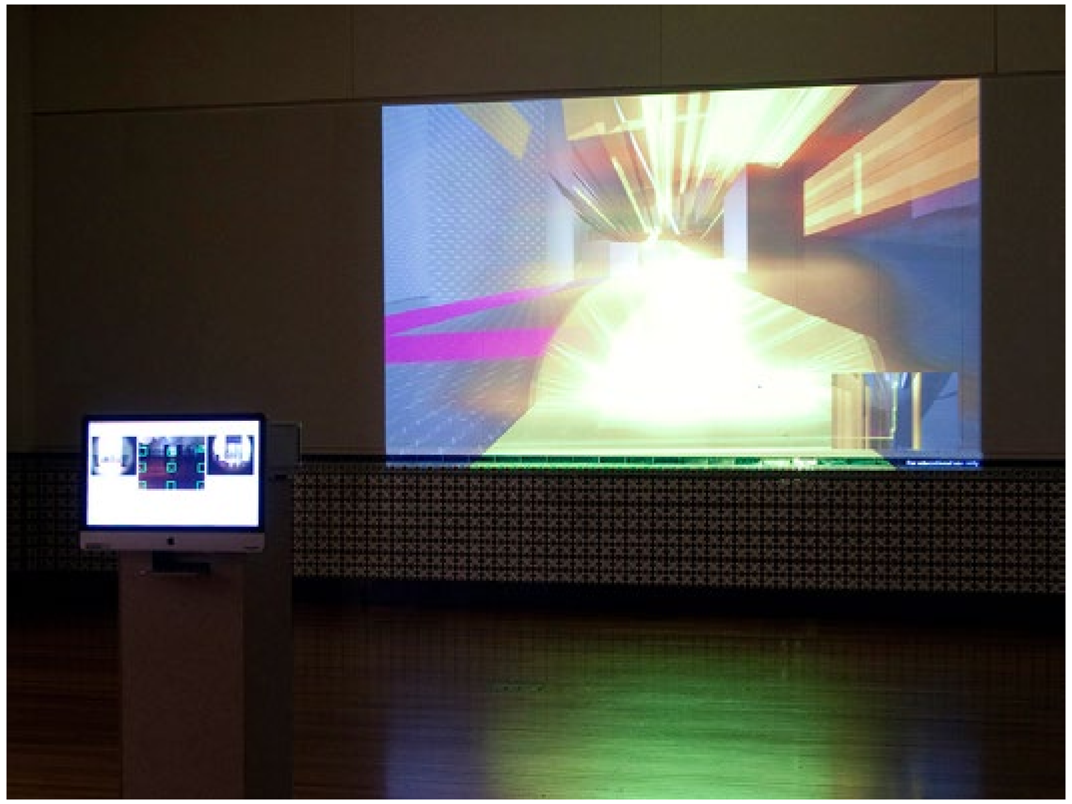


Figure 3.2.8
Space Trace (2011) installation Lux 2011 Wellington, showing a custom plinth housing a computer and sensors that control the navigation in a digital architectural model; an image is projected onto the wall, engaging the audience to experience the model.

Figure 3.2.9
Show Me (2013). A guide leading the user to a selected destination, leaving a breadcrumb trail. The guide provides a sense of scale during transitions to new spaces in the model.

3.2.6 and 3.2.7). These systems enable the technology to 'get out of the way', freeing the audience to engage with and experience the digital space.

Space Trace was an interactive projection installation work exhibited at Wellington Lux 2011. The installation consisted of a tall custom plinth with an iMac computer facing an audience, two web cameras, one facing outwards on each side of the plinth, and a powerful 6000 ANSI lumens projector on top casting an eight-metre-diagonal image (Figure 3.2.8). The web camera at the front of the computer was used to sense movement within the space, adding geometry with audio to the digital environment projected into the room. The side cameras changed the navigation path based on movement with the physical space. As people entered and moved about the room, the digital model dynamically changed its geometry and the navigated view of the model. The project was conceived to radically explore other navigation input controls for a digital model and to test multiuser controls.

Space Trace tested beyond the conventions of navigation input to explore alternative methods. The project offered input options such as movement in the real world via pixel isolation to control the navigation. Having no direct connection to control was disabling, turning users into passive spectators. Releasing the size of the viewable image from the desktop to dominate the wall directly affected the space with changing light and soundscape. The project extends the possibility of AI pathfinding. It is important to note that in the case of Space Trace, motion-sensing control of navigation was confusing to users. However, this is an area of research that could be developed further for installation and interactive work in museums and for other uses of passive fly-through videos of building designs.

Show Me

The preceding Navigation projects explored assistive techniques of navigating a digital architectural model, relying on a first-person perspective that offers the benefits of constant scaled view and integrated controls. Although a third-person perspective allows a constant reference of scale with an avatar, the avatar's geometry obscures the user's view. Switching between first- and third-person perspectives, adding another step into an involved navigation process, typically solves this. Show Me explores the concept of automatically providing a scaled figure while being led to unknown locations without the need for the user to have to manually switch perspective. In an attempt to aid understanding the scale of a building model while travelling, Show Me provides a scale person that computes a route to a preselected location and the user then follows the scale figure person to the location, like a personal tour guide (Figure 3.2.9). The user can automatically follow or manoeuvre themselves and follow the guide. The guide is used only when the user is shown the path to an unknown location, with the tour guide as the reference of scale. The addition of a guide or full-body avatar improves the estimation of

Name: Staff Room
Room #: 1.27
Level: A
Area: $49m^2$

Figure 3.2.10
Show Me (2013). Once inside a room, space-naming and coding information is displayed in the top-right-hand corner, allowing the user to make informed decisions.

distance (Mohler et al., 2008); however, the avatar can obstruct viewing when inside digital architectural models.

The Pointer project provided static room nametags located within each room at eye height that stay oriented to the viewer. The room nametags help provide a valuable understanding of location, when viewed from the correct location. These nametags proved useful only if the user was looking past the centre of the room. In a further exploration of the location-aware display of metadata, the Show Me project introduces the concept of location-based metadata. Each room or space has an unrendered collision volume that acts as a trigger to display key meta-information. As one enters a space, the room name, area, and room use (if known) are displayed, aiding in spatial cognition and reducing the incidence and duration of whiteout moments, shown in the upper-left-hand corner of Figure 3.2.10. The premise of this is that whatever space the user is in, information aiding the spatial comprehension of the proposed building would be clearly displayed. By providing location-sensitive metadata, users are informed of their location identity and function, thereby allowing focus on task execution. This method works while in first- and third-person perspectives, but when freely navigating with orbit and pan tools, understanding location becomes harder. A solution is for metadata to be displayed relative to the mouse cursor, but this would require further research beyond the scope of this project. By aiding awareness of location, users should be able to understand where they are, even in whiteout conditions.

After I observed a clash detection meeting at Cahill Contractors in San Francisco in June 2013, it became clear that even experienced people encountered moments of whiteout, interrupting the flow of the meeting. The meeting included representatives from the architects, contractors, structural engineers, mechanical engineers, and electrical engineers, connected via a teleconference system, viewing clashes found and displayed with Navisworks. The project was a multistorey, mixed-use building on a sloping site. The BIM model had been sliced into floor levels to enable quick clash processing. During the meeting, the defined clash results were selected and discussed. Navisworks provides transition between clash results, maintaining orientation in the model. However, while reviewing the results, the majority of the results were characterised by someone asking what was the location of the clash or what room was the clash in. On several occasions, someone had to refer back to the drawing set to determine the location and conditions of the clash. This could have been due to a number of factors, including: not viewing the transition between results, the final view being focused on the clash, and an undeveloped spatial understanding of the project. It became clear at the meeting that key information needed to be displayed about the spaces affected by the clash, not only the location of the clash in the building. The location of a clash directly affected the resolution. One example during the meeting was a light fixture clashing with a duct: the conversation started with the assumption that the clash location was a publicly accessible space; however, after further investigation, the clash was in fact found to be within a service space, with the solution being very different compared with a front-of-house location. At no point were location-aware metadata displayed that would have helped people avoid experiencing whiteout conditions, thereby keeping the meeting flowing smoothly. Displaying the metadata of a space beyond the room number, including area, programme, and function, would help inform the process of clash resolution.

Show Me sets out further scope to explore the implications of location-sensitive metadata. The Te Ara Hihiko project in Section 3.3 begins this exploration. The addition of a tour guide may be productive depending on the user's background and experience: somebody with no architectural knowledge may find the support useful, but an experienced architect may become frustrated with the guide. Since this project was completed, select BIM review softwares have included the display of basic space name and number information, but access to further relevant data would help users to better locate themselves.

Section Summary

This section explored methods of aiding navigation with assistive wayshowing by introducing AI pathfinding transition through the interiors of the models. This involved moving beyond transitions between predefined views that consider the model or building as an object, to views that consider the model as an interior space with walls, floors, ceilings, and rooms. The transitions are triggered by the selection of a fixed or defined view (e.g., elevation or perspective view), providing a spatial context and relation of the new view. A critical way we develop cognitive maps of spaces is how we move through them (Waller & Nadel, 2012). These spatially responsive transitions aid spatial cognition beyond teleporting, and direct rotation between views, allowing users easier access to building information.

Building on the Pointer project, the Pathfinder project explored spatial transitions beyond quick direct animation from one camera view to another, responding to the building's geometry to create spatially aware transitions, thus aiding in the development of people's cognitive maps. The transition between defined interior locations was also considered in relation to how we experience real space. While viewing the building, an important location could be selected and a walkable path to the location could be generated using AI pathfinding. A guided transition to a defined location enables a user to understand the relationships of locations, including the distance between locations and other key observations along the path. Although an overview of an interior can be gained from a plan, it can take years of training to understand the experience of an interior from a plan. By enabling spatially aware transitions, people will be able to experience the spatial quality of a building, and even experienced people will be able to understand spatially complex buildings more easily than when based only on drawings.

After critically reflecting on the Translation projects and Navigation projects, I was led to the conclusion that the amount or level of model detail influences spatial cognition. This need not necessarily be realistic representation; rather, it may be the resolution of the modelled geometry and the detail of content modelled. The more physical information that can be digitally represented, the easier and more accurate the spatial cognition becomes. This is problematic, because an increased number of polygons directly impedes responsiveness. One method used to increase responsiveness is by controlling a user's view frustum, reducing the distance of the far clipping plane to limit the polygon count. A more advanced method is to control the display of geometry detail relative to the viewer's distance, referred to as the level of detail. If the viewer is far away, then only basic model information is displayed, and the closer the user becomes, the higher the level of detail that is rendered.

Figure 3.3
Antarctica: The Grain of White #12 by Anne Noble (2009)

3.3 Distance Projects

Projects:
- Te Ara Hihiko
- Odograph
- Your Grid
- Measure

Navigation tools:
- Mouse walk
- WASD walk
- Mouse look
- AI pathfinding
- Guided path
- Automatic path transition
- Distance travelled
- Reference grid
- Measurement

Research methods:
- Case study
- Experimentation
- Exploration
- Critical Reflection

Technical assistance:
- Oliver Blair

Whiteout conditions, defined by airman Robert Boswell, result in the loss of depth perception:

> *Only two conditions are required to produce whiteout, a diffuse shadowless illumination and a mono-coloured white surface. Whiteout… is not associated with precipitation or fog or haze, the condition may occur in a crystal clear atmosphere or under a cloud ceiling with ample comfortable light and in a visual field filled with…objects.…Those who have not been exposed to whiteout are often skeptical about the inability of those who have experienced it to estimate distance under these conditions. (as cited in Mahon, 1981)*

Robert Boswell's last sentence of the aforementioned quote introduces the effect that whiteout conditions can have on the estimation of distance (Figure 3.3). It is common to experience moments of whiteout in digital models, leading to disorientation and difficulty navigating. In this section, I develop four projects that aid distance cognition.

The design research conducted in the Translation projects in Section 3.1 and the Navigation projects in Section 3.2 uncovered the importance of improving spatial cognition within digital architectural models and showed that the way in which we interface with digital models is still in the infancy of development.

An understanding of distance within digital models is a critical element for aiding navigation and spatial cognition but one that has received less research attention compared to spatial orientation and location awareness in digital environments. Research has focused on the accuracy of distance estimation without providing any tool set to support the estimation of distance and scale (Loomis & Knapp, 2003; Mohler et al., 2010; Ries, Interrante, Kaeding, & Anderson, 2008; Turner & Turner, 1997) and the perception of travelled distance (Terziman, Lecuyer, Hillaire, & Wiener, 2009). The Distance projects set out to explore methods of providing quick and simple indications of distanced travelled and of the size or scale of view currently being examined.

A common use of digital architectural models is in BIM. A critical part of the BIM process is a review of the completed building models. BIM reviewing software enables dimension take-off as a standalone function; however, this is a cumbersome method for comprehending the scale of a building model of which the user is inside. The use of view-in-view location maps or plans provides only limited assistance with understanding distances, as no clear indication of scale is usually provided and such maps or plans are typically not at the same scale as the first-person perspective. The view that a user takes of a BIM model changes frequently, either controlled by the user or by someone else. In the process of changing view, the distance of the camera to the model also changes, which adjusts the scale of what is being viewed. In this section, I discuss methods of understanding and aiding distance cognition inside digital architectural models. The first project, Te Ara Hihiko, examines the mouse walk tool with unguided and guided pathways. The second project, Odograph, displays total distance travelled and distance since the last stop. The third project, Your Grid, introduces a spatially responsive grid to aid distance estimation. The final project is Measure, an investigation into fast distance measuring within a digital architectural model.

Te Ara Hihiko

“Te” means ‘the’.
“Ara” means ‘way’, ‘path’, ‘lane’, ‘passageway’, ‘track’, ‘course’, or ‘route’.
“Hihiko” translates as ‘brisk, cheerful, and inspired’ and infers a sense of ‘positive energy, innovation, and creativity.’

This project examines the functionality of the mouse walk tool against different levels of guided navigation. This was achieved by recording the orientation and wayfinding of 12 participants exploring a three-dimensional digital architectural model that provided wayshowing and location showing in relation to three given tasks. The journal article by Professor Bowman and co-workers entitled ‘A Methodology for Evaluation of Travel Techniques for Immersive Virtual Environments’ (1998) identified the following performance

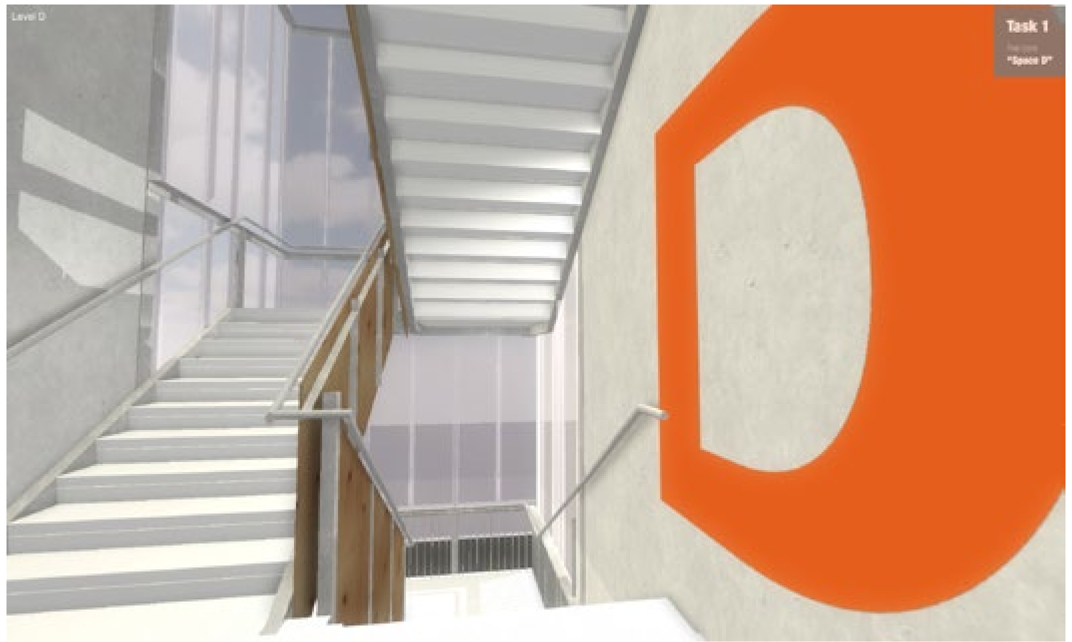


Figure 3.3.1
Te Ara Hihiko (2013) mega wayshowing type denoting the physical building floor level, which is provided in the digital model to support users' wayfinding and navigation.

metrics: Speed (task completion time), Accuracy (proximity to the desired target), Spatial Awareness (the user's knowledge of their position and orientation within the environment during and after travel), Ease of Use (the complexity or cognitive load of the technique from the user's point of view), and Information-gathering (the user's ability to actively obtain information from the environment during travel). These metrics are used to help explore the question of how spatial orientation and an understanding of location can be improved in three-dimensional digital models.

The design of the project exposed people to three tasks of navigation and wayshowing to test the feasibility of the methods and procedures used to record the movement and spatial awareness. An exploratory computer model of a new five-storey building was created and optimised for participants to access it online. The model was created in Revit, by the architects, then exported to SketchUp, where model optimisation was performed to reduce polygons and to apply material textures. A custom interface and navigation system were created in Unity, a three-dimensional game engine. Environmental enhancements were added, including realistic material textures, the building's wayfinding design (floor levels), clouds (skybox), artificial lighting, sun, and shadows, all to aid in orientation and spatial readability.

The project used the digital model created by Athfield Architects for Te Ara Hihiko, a new five-storey creative arts building for the College of Creative Arts, Massey University, Wellington. Built into a steeply sloping section of land, entry points are possible on three different levels. The university uses letters to denote building floor levels, which may initially confuse visitors. In Te Ara Hihiko, a feature has been made of the five letters, A, B, C, D, and E, thus introducing new visitors to this concept quickly as they enter the building. The wayshowing, designed by Nick Kapica, relies on the placement of mega typography within the built environment not only to communicate the required building information but also, in doing so, to engage the viewer in visually understanding the space (Figure 3.3.1). The participants all knew of the building and had been inside parts of it. Consideration of participants' familiarity with the building was resolved with the selection of obscure rooms for each task. A recording was made of each participant's use of the navigation tool.

The project explores two travel techniques drawn from the Evaluation of Travel Techniques for Immersive Virtual Environments by computer scientists Doug Bowman and co-workers (Bowman, Koller, & Hodges, 1998). The selected techniques responded to the current standard CAD/BIM software mouse command of click and drag to 'walk'. People were limited to this method of movement in order to explore how they use this often-under-utilised tool. A 'look' command was also provided. The free-form travel was supplemented

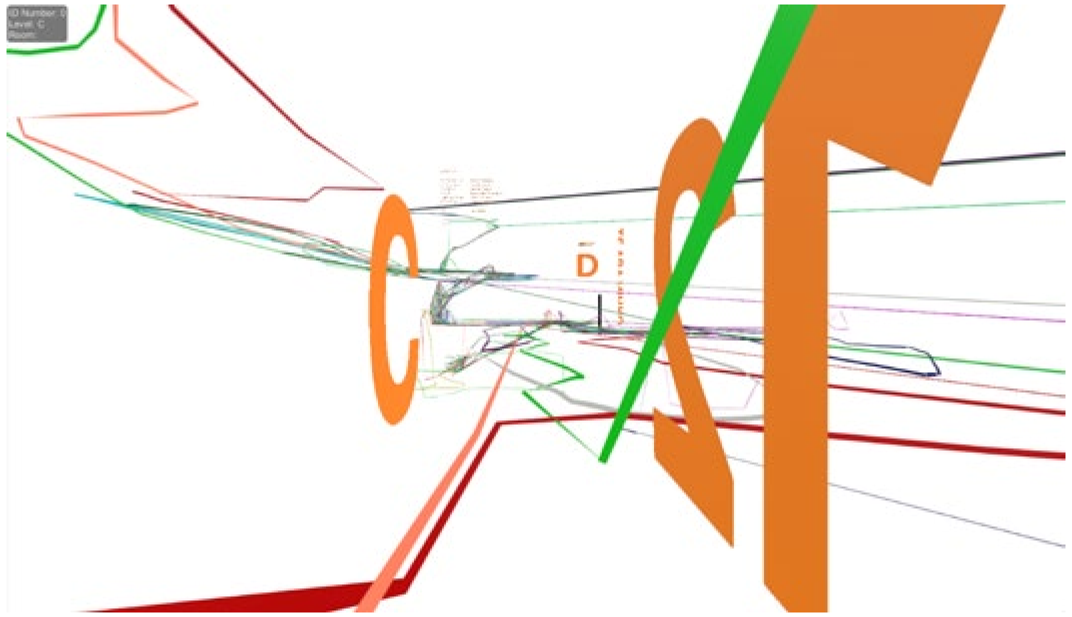


Figure 3.3.2
Te Ara Hihiko (2015), showing all participants' paths travelled displayed alongside building wayshowing, without building model geometry. The paths highlight the differences in participants' routes.

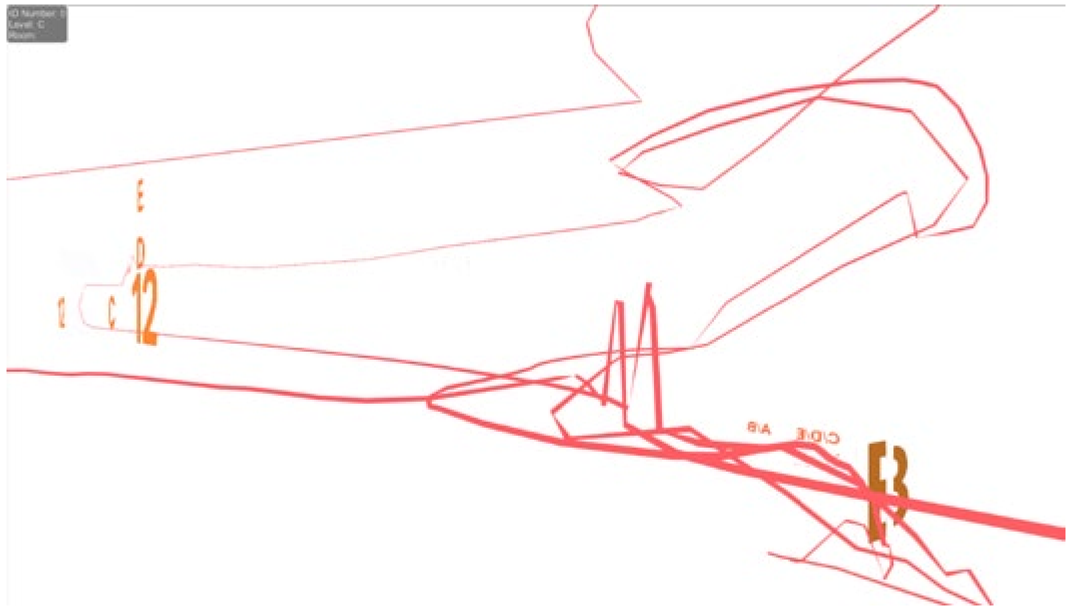


Figure 3.3.3
Te Ara Hihiko (2015), showing one participant's route traced in three-dimensional space, with the building's wayshowing, without building model geometry.

with a guided or recommended path and a dynamically created AI path. The second travel technique was a fully automated AI directed path that takes the participant on a completely guided walk to the specified location.

The guided AI system leveraged the Unity AI pathfinding technique to dynamically generate a line showing the shortest walkable path to the target room's location. An invisible controller is spawned at the participant's location; the invisible controller then travels to the target location at walking speed, leaving a coloured graphical line showing the path. The intention is for the participants to follow this line as it travels towards the target.

The second fully automated travel technique used the same Unity AI pathfinding as the first; however, in this scenario, the player is the travelling AI controller, led automatically to the target location. As well as this, the player automatically looks in the forward direction while travelling. For both of the AI systems described here to function correctly, the digital model geometry had to be carefully selected to affect the AI navigation mesh, as the system is dynamic and needs to be able to be triggered from any location in the level. Floors, doors, and stairs all needed to be specified as navigable by the AI navigation mesh system, whereas walls, balustrades, and handrails were specified to block the AI pathfinding system.

The movement of the participants' travel through the architectural digital model was recorded, tracing their speed and the direction of their view, while they undertook three specific tasks. A custom position-tracking system was created for this study. The system utilised the JavaScript, HTML, and PHP languages to output participant positions from the Unity web player. The web player was embedded into a PHP page and uploaded to a remote server, outputting the time, position, and rotation of each unique participant movement as arguments to a custom PHP function. This PHP function created a unique text file on the remote server for each participant session, writing the unique player movement values to a new line (Figures 3.3.2, 3.3.3, and 3.3.4 show the recorded data on participants' movements).

At the end of the study, the text files were downloaded from the remote server and loaded locally back into the Unity project by a custom JavaScript that reads each text file line and generates a point along a uniquely coloured line. The loading script also generated arrows for each point in the player path, where the size and direction of the arrows indicate the time difference between the previous point and the direction of the player, respectively.

The three tasks were designed to get the participants to find given locations via different navigation methods. The tasks provided movement across multiple levels and different types of spaces that most participants would not have previously entered or known of in the physical building. Task one

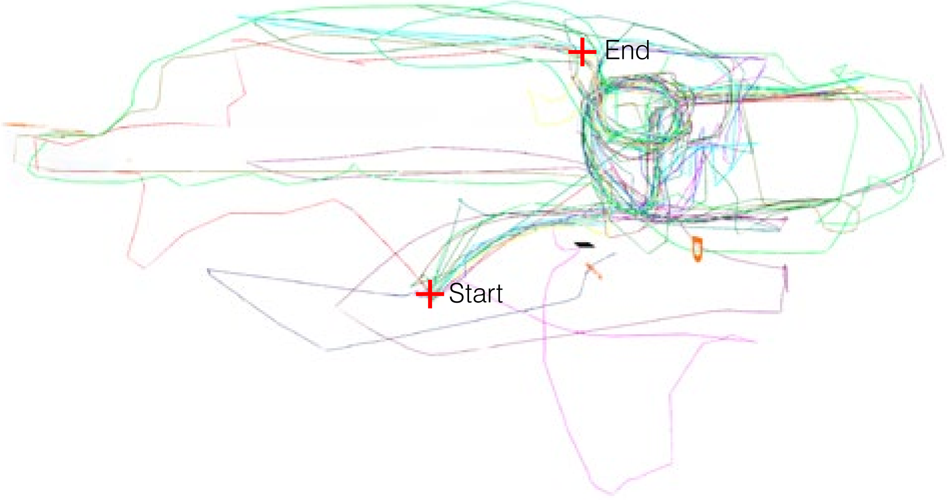


Figure 3.3.4
Te Ara Hihiko (2015), showing all participants' paths travelled displayed in plan, without building model geometry. The paths at the top of the figure are participants' routes searched for Task 1, Space D.


ID Number: 735
Level: C
Room:

Task 1
Find:
Studio D

Figure 3.3.5
Te Ara Hihiko (2015, showing an example of the task interface.

used only standard mouse-controlled walking and looking tools, with the participants' current room and level information being given in the top-left-hand corner of the web player frame (Figure 3.3.5). Task two used the same navigation tools and current location with an AI trail to follow. Task three was an AI-generated auto-walk option that guided the participant automatically to the destination. The tasks were as follows:

- Task 1: navigate to room Studio D (a large open space on Level D)
- Task 2: navigate from room Studio D to Studio B (a small studio space on level B).
- Task 3: navigate from Studio B to the studio E on Level E.

The participants recruited from the Wellington Revit users Group, were directed to a web page that contained an interactive view of the digital building model in a Unity web player frame with instructions and a questionnaire below. The participants were then able to interact with the model, which provided instructions for each task. The digital model was setup to automatically record the path travelled, speed, and direction of view of each participant. The recorded data points were based on the performance metrics set out by Bowman et al. (1998), as outlined below.

Speed (task completion time) and accuracy (proximity to the desired target) were both automatically logged based on movement in the digital model, and no participant action was required. Spatial awareness (the participant's knowledge of their position and orientation within the environment both during and after travel), ease of use (the complexity or cognitive load of the technique from the participant's point of view), and information gathering (the participant's ability to actively obtain information from the environment during travel) were collected via a questionnaire and automatically logged as above. The ease of use ('how easy did you find navigation for the task?'), spatial awareness ('how well did you know your position and orientation during and after the task?'), and information gathering ('how perceptive of the building were you while moving for the task?') were collected via the questionnaire, see appendix 2.

The results for the tasks were as follows. For speed and accuracy, the time spent on tasks 1 and 2 varied significantly, ranging from 56 seconds to almost 13 minutes for task 1 and from 53 seconds to just over 2 minutes for task 2. This reflects participants' ease of use and direction of view at the start of task 2, as some would have had difficulty in locating the AI path to follow. The average time for completing task 1 was 3:10 minutes, for task 2 was 1:24 minutes, and for task 3 was 53 seconds. Tasks 2 and 3 had a high number of short times compared with task 1, clearly indicating the improvement that AI path finding and showing has on navigation and accuracy. The paths of all participants were overlaid back into the digital model and clearly show the diverse routes of the participants for task 1 and the alignment for tasks 2 and 3 (Figure 3.3.4).

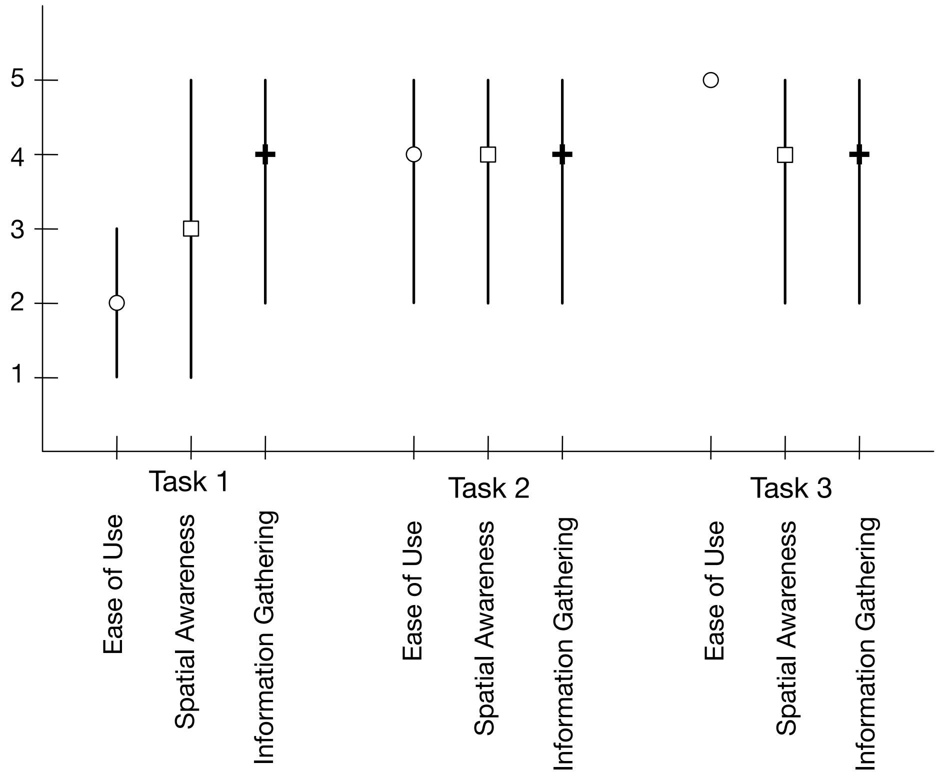


Table 3.3.1
Te Ara Hihiko (2015) ease of use, spatial awareness, and information gathering range and average responses for each task.

The average ease of use score for task 1 indicated that the common navigation tool was rated towards the difficult end of the scale. The average rating for task two lay towards the easier end and task 3 had an average rating of easy. This followed initial expectations, with a large difference between task 1 and task 2 because of the learning curve of task 1 and the addition of a guided path to follow. Task 3 had the highest ease of use because of the automatic AI path. Comments from the participants regarding ease of use noted that the mouse-controlled walk tool was difficult; this was reflected in the data. One participant suggested using WASD or arrow keys for controlling walking.

The spatial awareness of task 1 had an average of 3 out of 5 with a full range of 1 to 5, tasks 2 and 3 of averaged 4 out of 5, measured using a five-point scale ranging from 1 ('no idea where I am') to 5 ('know exactly where I am'), see table 3.3.1. This is an encouraging finding as it was predicted that task 3 would have a lower spatial awareness compared with the other tasks. It is considered that tasks 1 and 2 helped in the participants' spatial cognitive mapping of the building. The order of the tasks should be reconsidered in future studies. Because of the automation of task 3, it was presumed that spatial awareness might have been lower than the other tasks. The fact that task 3 showed similar or greater spatial awareness to that of tasks 1 and 2 may be because of the reduced focus required by not using the 'walking' tool in task 3, which allowed the participants to give more attention to spatial awareness and information gathering.

Information gathering rated from 1 ('unperceptive') to 5 ('very perceptive'). The study showed that all the tasks had the same average rating of information gathering (4 out of 5) while moving, with the same range lowest of 2 and highest of 5, see table 3.3.1. While each task provided different navigation support, information gathering was not directly affected. Participants' commented that it was difficult to find the destination in task 1. It is important to note that there was a spread of increased and decreased information gathering across the tasks, reflecting that people have different perception. To gain further insight the study would need to be carried out with a larger group and to randomise the sequence of tasks.

Both during and after the completion of the study, there were clear difficulties identified that will be improved for future research. Task 1 resulted in a learning period for the mouse-controlled walk command, and therefore the ease of use was rated lower than in task 2. Future studies will explore randomising the order of the tasks as well as increasing the number of participants. The relationship between actual recorded data and subjective data from the questionnaire requires further analysis, which was not covered here. Recording the time taken for each task required a manual process of locating each task's completion coordinates; future studies will automate this within the custom code.

○ Crosshair
○ 3.4 Measure Distance:
○ 3.3 Your Grid
○ 3.3 Fixed Grid
● 3.2 Odograph
Total: 56.8m
Last path: 5m
Paused: True

Figure 3.3.6
Odograph (2014) records and displays the user's total distance and last distance travelled, to allow correct comprehension of the scale of a building.

The results clearly show that participants found the common mouse-controlled walk tool difficult to navigate with. The addition of AI paths to follow and automatic spatial walking transition between spaces greatly improved the ease of navigation and enhanced information gathering. There was no change in spatial awareness over the three tasks. The study did not have a true base line as per most uses of BIM for post-design. The participants were provided with the building wayfinding, indicating floor levels and the interface showed their current floor level and room name, which aided in improved spatial awareness.

Odograph

This project aimed to provide a clear method for measuring how far the user has travelled since their last resting place, and if the destination is predefined, to display the distance remaining to travel in real time to help build a scaled cognitive map. The concept behind providing distance information is to help draw connections across a digital model so that we can develop correct relationships between spaces and views of the model, thereby developing spatial awareness. Huth (2013) states that navigation can be divided into three key abilities: to understand spatial orientation, to accurately estimate distance, and to correctly spatially locate oneself. Odograph sets out to accurately aid distance estimation while navigating inside a digital architectural model, displaying the total distance travelled, the last distance travelled, and indicating whether the user is moving or still (Figure 3.3.6). By providing an accurate gauge of the total distance travelled, the scale represented by a model can be understood. Although a trained architect may know this intuitively, it is not always the case. People without the spatial training of an architect or builder experience these models with a different understanding of spatial scale. This is similar to the way in which many people are unable to understand architectural drawings. A more immediate distance cognition is the distance a user has travelled from their last resting location, and allows a quick assessment to be made of the distance between two rooms or the length of a single space. These distances help to build a scaled cognitive map of a building model by quantifying an experience that is typically forgotten about. The interface also displays whether the user has paused long enough (or not) to trigger a new segment of measurement, indicating a break between distances.

When viewing a digital architectural model, predefined views have commonly been created, based either on major drawing projections such as plans, sections, elevations, and perspective views or on clashes detected and requiring resolution. Some software provides a spatial transition between the defined views, whereas others jump instantly between views. The spatial transition helps orient and locate people if the correct transition is used. What is not clearly represented is the distance travelled between views. Knowing the distance between views helps in building an accurate cognitive map.

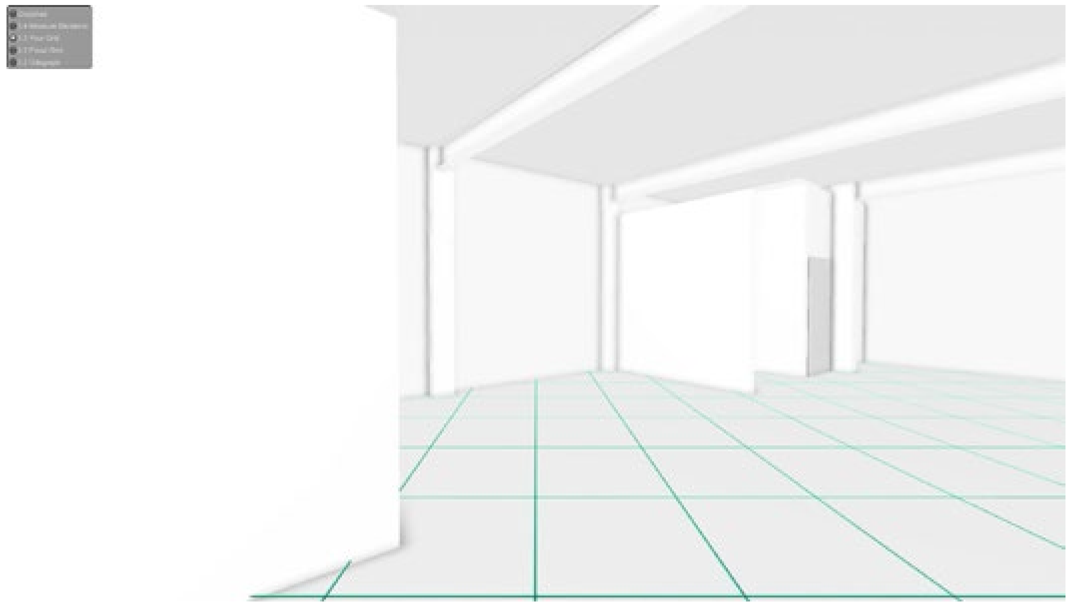


Figure 3.3.7
Your Grid (2014) locates a 1-metre grid at the nearest floor level to the user's location, which can be rotated to align with their view. The grid can be set to appear only while stationary so as to enable unobstructed navigation.

Your Grid

Grids are "one of the oldest architectural design tools" (Gross, 1991, p. 33), and have been and continue to be used for designing the location of architectural elements. At some point in the late nineteenth or early twentieth centuries, a datum matrix became a convention for locating a dimensional reference system (Wakita & Linde, 2003, p. 287) or what is commonly referred to as the column grid or building grid. This grid establishes a datum for major structural elements and can be represented in plan, section, and elevation views. The column grid is a powerful ordering device and important locating mechanism, often the key origin device in plan drawings that functions when an overview is possible. When inside a digital architectural model, the column grid is usually obstructed or not visible at all. Related to the (lack of) visibility of the column grid is a lack of a consistent distance between lines, due to the relationship of the column grid to the building structure. With architectural drawing sets, a clear order of view and context is constructed from plan views, elevations, and sections, down to details. The plan or section provides the overarching context, but such context can be easily lost inside a digital model. With respect to spatial cognition, these limitations can confuse a person viewing the interior of a model. The premise of Your Grid is to provide a standard one-metre grid that is located between the viewer's position and the nearest floor level. The project seeks to provide an egocentric one-metre square grid that can be used to gain a sense of scale (Figure 3.3.7). The grid is centred on the viewer to quickly give the correct size of what is currently being viewed, either an exterior view, or a tight interior view of structural elements.

Your Grid differs from existing grids in three-dimensional software, which are oriented around the origin of the digital environment (0,0,0). Once inside a building model, these grids are obstructed, rendering them ineffective in aiding spatial cognition. Autodesk proposed a smart multiscale reference grid (Glueck et al., 2009), as discussed in Section 2.3, which also stays fixed around the origin plane, responding to the scale of what is being viewed (for example, drawing the grid at millimetre intervals when viewing a small object or at kilometre intervals when viewing a city). Your Grid is set at a constant scale, a metre grid (or yard), a building scale, which allows a viewer to quickly understand what is being viewed. When a viewer is focused on a detail, it quickly becomes clear that the view is scaled under a metre, or looking out across an open room the size can be estimated by counting the grid lines. Your Grid provides a frame of reference to understand the scale of what is being viewed. This contrasts with the observation that "typical three-dimensional software applications do not account for the scale of the environment within their navigation tools" (McCrae et al., 2009, p. 7).

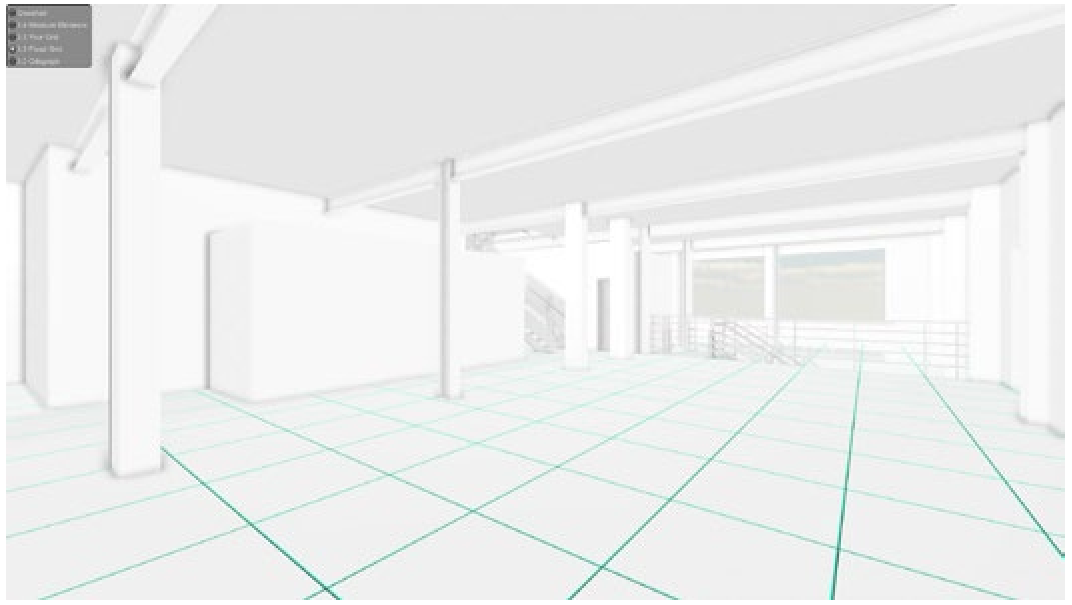


Figure 3.3.8
Your Grid (2014) can be set to align with the building and to stay fixed while navigating, providing a constant scale reference.

Figure 3.3.9
Measure (2014) uses a one-click distance measurement, based from the location under the crosshair when the mouse's right button is clicked, to wherever the crosshair is then located.

Your Grid can be configured to appear only while still or to follow the viewer as they navigate through space. Once stationary, users are able to adjust the grid's rotation to allow it to align with key elements (Figure 3.3.8). Further spatial clarity can be gained by combining Your Grid with the functionality of the Show Me project to display location-aware metadata such as room name and room area.

Measure

Measure project is an attempt to provide a fast method for estimating distance. Typical dimensioning tools can be categorised into two types: a formal dimension that appears on working drawings, or on the model itself. The second method is comparable to a tape measure, allowing one-off measurements to be made between two points. Both tools require multiple mouse clicks to return a result, which can be off-putting for people when trying to quickly comprehend a room size. The concept behind Measure is to always reference from crosshairs in the centre of view so as to gain quick estimations between the crosshairs on the activation of Measure and to whichever surface the crosshairs roll over (Figure 3.3.9). This provides another form of aiding distance estimation while developing spatial comprehension of a building.

Section Summary

Although "there is no one proper way to navigate" (Huth, 2013, p. 8), an understanding of distance helps to appreciate the complex behaviour of navigation. We all have different abilities of navigation and spatial cognition that impact on our experience inside digital architectural models. The navigation tools that allow us to explore inside digital environments also influence our experience. In this section, I explored the mouse walk tool by testing three levels of aiding location-finding. The aided pathways, which highlight the benefits for spatial awareness and the improved ease of use of location-aware relative distanced paths, assist people to spatially understand a digital model. With further explorations of aiding distance estimation, the projects of Te Ara Hihiko, Odograph, Your Grid, and Measure demonstrate enhanced methods of supporting spatial cognition within the interiors of digital architectural models. These projects began to establish an important area, that of aiding distance cognition within digital models, reducing whiteout moments, each project offers a specific identification of distance, Odograph allows understanding of distances travelled benefiting comprehension of scale between rooms, Your Grid provides a spatial grid that intuitively shows the scale of a room, and Measure allows a simple tape measure that users can check unknown sizes, all building an accurate cognitive map.

Figure 4.0
Williams Field #3 by Anne Noble (2002). Emerging from a whiteout being guided by a row of small flags, up ahead on the left-hand side, flapping in the wind.

4 Discussion

Showing the way

In this chapter, I reflect upon the contribution that the design investigations offer our understanding of spatial cognition via navigation within digital architectural models.

Exploration

Navigating the unknown is hard. Navigating within digital architectural models is harder. In my research, I sought new approaches to design methods of navigating digital architectural models to gain enhanced spatial cognition. Using a reflective practice methodology of project-based design investigations, the research explores aiding distance estimation and wayshowing methods that allow spatially aware navigation tools to reduce moments of whiteout. Figure 4.0 shows traces of people's movement across the Antarctic plateau and small flags guiding their return travel through whiteout conditions. I have taken distance, one of John Huth's three elements of navigation (Huth, 2013), and explored methods of aiding an understanding of distance across various architectural interface investigations. In the following pages, I reflect upon how these project investigations contribute to our understanding of spatial cognition inside digital architectural models. I argue for the importance of aiding distance cognition and of spatially aware navigation tools in improving spatial cognition by reducing whiteout conditions. In addition, I discuss the implications of the findings for research and practice, and identify the limitations of my research. I also set out a framework for improving spatial cognition inside digital architectural models.

The architecture and construction industries are in transition from a two-dimensional workflow to multidimensional data-driven processes. I argue the need for improved navigation tools in this transition. There have been small improvements over the time period of my research, with the inclusion of collision-aware first-person navigation tools and widgets like Autodesk's ViewCube, alongside research projects that have investigated improvements, predominantly for exterior navigation (Fitzmaurice, Matejka, & Mordatch, 2008; McCrae, Mordatch, Glueck, & Khan, 2009). The continuing navigation problems are highlighted in Chapter 1. There has been little investigation into the improvement of interior navigation of digital architectural models. Table 4.1 details the navigation methods investigated in each group of projects.

The future of architecture and construction requires more than a direct translation from two-dimensional workflows into multiple dimensions, rather, a complete rethink of the new opportunities that the BIM process offers. The development of automated three-dimensional clash detection is an example of a process that has developed from manual detection (by painstakingly

Translation Projects	Navigation Projects	Distance Projects
Section	Pointer	Te Ara Hihiko
Layer	Pathfinder	Odograph
VQ6	Space Trace	Your Grid
Pekapeka	Show Me	Measure
Navigation Tools Explored		
WASD walk	WASD walk	Mouse walk
Mouse look	Point to walk	WASD walk
Model interaction	Mouse look	Mouse look
	AI pathfinding	AI pathfinding
	Guided path	Guided path
	Automatic path transition	Automatic path transition
	Breadcrumbs	Distance traveled
	Metadata display	Reference grid
		Measurement

Table 4.1
Diagram of navigation tools investigated in each group of projects created for this research.

overlaying two-dimensional drawings and visually checking for clashes with infrastructure that may not even be drawn) to a new automated process that has changed how construction companies manage clashes of building infrastructure. This shift has seen improved construction times and reduced clashes onsite, but has introduced new moments of whiteout in the process of resolving clashes. It is not entirely clear what new approaches will be developed in the translation to multidimensional workflows, but it is clear that spatial comprehension will be important. To improve spatial cognition within digital architectural models, multiple elements need to be improved, with the key element of distance estimation needing more attention. In addition to improving distance estimation, there is a need to increase architectural model detail and the use of other identifiable elements, such as furniture, rather than creating more realistic environments. This has started to occur as computational power has increased. However, there has been no guide around the optimal use of detail. Also lacking has been an acknowledgement of people's spatial differences, which should lead to the need for different types of navigation-aiding, as explored by Autodesk Research (Fitzmaurice et al., 2008). With the predicted increase in data (Eastman et al., 2011) expected from the amount of detail that will be embedded within BIM models, how can the data become location aware inside accessible digital models? It is also important to note the design of a building with respect to a refined consideration of architectural wayshowing to help spatial cognition in both the physical and the digital worlds.

Locating Limitations

The design investigations discussed in Chapter 3 have all been conducted only within computer game engine software. Each platform offered many benefits while also placing restrictions. It would be beneficial to test across a wider range of platforms, such as proprietary BIM software, offering other methods of rendering to allow further comparison. The level of realism may be seen as a limitation, and my research concludes that attention to detail is of more value to spatial cognition than is striving for realism. The Translation projects revealed that animation of a building's geometry could provide clarification in the building process only if used in carefully considered ways, because an animation can easily be misinterpreted.

The projects conducted in this study covered a large range of variables in an attempt to enable a rigorous measure across multiple game engines, multiple building configurations, render quality, model complexity, and level of detail. This research did not focus on user testing, in part because of the complexities of the early software platform requirements, which resulted in unstable interfaces. The Te Ara Hihiko project was created to test how people navigate with the mouse walk tool, and provided useful results that established a productive method of testing for the other projects. This project enabled people to interact with the model on their own Internet browser, and did not need a specific location or specialty hardware (a recent software development). This is an area I believe will see increased research attention, creating a live record of how people interact within digital models, similar to Internet analytics or the information that is being recorded in some retail and entertainment environments (Davis, 2014), but in this case measuring the building. It is important to note that all the participants in the Te Ara Hihiko project had been inside parts of the actual building before. Although the spaces selected were unknown to them, they all had an existing but incomplete cognitive map. It would be prudent to perform this study again with an unbuilt building and using more participants.

The software platforms explored and investigated in my research are still the largest limitation in trying to improve navigation tools. Of the four specific software titles used in the projects (and many others available), each has critical elements that limited their full potential. This includes proprietary platforms that do not allow exploration beyond those accessible in the software or as stated by the end-user license agreement. Each of the three-dimensional softwares that I used limited the research in its own way: limited user interaction, limited usability, limited representation, limited rendering, or limited geometry.

My research confirms and builds on the investigation by Autodesk Researchers' to design a safe three-dimensional navigation experience as introduced in Section 2.1, including the following: provide orientation awareness, enhance tool feedback, offer pre-recored navigation, prevent errors, and recover from errors. "While many existing navigation tools offer some of these properties, it is important to realize the need to provide all of these properties at a rich level to achieve a rewarding navigation experience." (Fitzmaurice et al., 2008, p. 9). Within this research no single method or navigation tool will be enough on its own to improve the spatial cognition experience, but rather will require a closer interconnection between the currently available methods alongside further development of the proposed methods investigated in this exegesis.

Distance

Understanding the size of what is being viewed within digital architectural models is critical to understand the content. There has been limited research on this area of navigation within virtual reality environments, and has focused mostly on testing the estimation of egocentric and exocentric distances, rather than on the development of tools to aid in distance estimation. Within architectural drawings, this has been achieved mainly via drawing at conventional scales and dimensioning key elements, processes that have developed over hundreds of years. Within BIM models, conventional scales are used only for two-dimensional drawings once printed. Distance cognition can be improved by including spatially aware transitions and providing tools such as Odograph and Your Grid to establish new digital conventions. Understanding distance within digital architectural models is essential for improving how people comprehend architectural projects to avoid moments of whiteout, which can result in misunderstandings and expensive mistakes.

Building Detail

The level of detail of a digital architectural model directly affects our spatial cognition. Historically, the amount of detail that can be modelled is influenced by the size of the project and the computational processing power available for visualisation. These aspects are changing with the increased use of BIM and the development of software. Critically reflecting on both the design projects and the literature, it became clear that the level of detail within the digital model plays a critical role in informing how we read the scale of what is being viewed. The research conducted prior to and during the 1990s can be categorised as involving very primitive environments that directly affected people's reduced spatial cognition when compared with reality. There needs to be a focus on detail rather than on realism by modelling elements that clearly express their size, such as stairs, balustrades, handrails, and light switches, in comparison with elements whose size is difficult to understand, such as floors, walls, ceilings, and structural members. Further research into the required level of detail needs to be conducted, including whether it differs from that required within two-dimensional drawings.

Difference

It is important to note that no matter which navigation tools are provided, spatial abilities vary among people (Hegarty & Waller, 2005). Everyone has a different capacity and comprehension inside digital models, resulting in different cognitive maps and the need for different methods of navigation. Although some people may not need any help with navigating inside digital models, others require support. Architects, for example, come with a variety of skills for working within digital models, from a background of designing space, compared to someone who has never needed to generate a cognitive map for a unknown space, or people who have grown up inhabiting many different digital environments. Children as young as five are constructing interactive buildings in virtual environments such as Minecraft, a video game that allows players to construct out of textured cubes. However, no matter what your abilities are, there will still be moments of whiteout that need tools to reduce them and to enable rapid recovery from them.

Building Data

Digital architectural models are rich in useful data that can benefit navigation and spatial cognition, and the amount and quality of data will continue to increase over time. BIM models are increasingly including data on schedule, quantities, cost, and building operation. These data can frequently be difficult or impossible to access while navigating within the geometry of a model. Room number and name, room area, and room function are examples of metadata that are commonly embedded within a BIM model and which are difficult to access; such metadata could be leveraged to help people locate themselves. However, these still require a location-aware translation from room labels on a plan or section into an interactive three-dimensional environment.

In a similar way to the tracking of users' website navigation and, more recently, of users' movements through retail and entertainment spaces, digital architectural models could benefit from recording and embedding spatial user analytics into the software. The ability to record and visualise how people interact with a digital architectural model could be incorporated into the design process, enabling fine-tuning of architectural wayshowing, and this would result in improved navigation and spatial cognition in both digital and physical spaces.

Architectural Design

The design of buildings has an impact on how we navigate in both the digital and physical worlds. The work of Kevin Lynch (1960) and Romedi Passini (1984) established productive methods for improving architectural wayshowing, which are often forgotten by designers, who completely comprehend the building. Although navigation may work in plan, people do not experience a building this way. By providing architectural elements, including formal, visual, acoustic, and logic elements, to aid people's navigation, improvements in spatial cognition in both the digital architectural model and the physical building are possible.

Knowledge Contribution

My major contribution to advance knowledge is providing a framework for navigation tool design and wayshowing strategies to improve spatial cognition inside digital architectural models. Navigation tools need to move beyond the objectification of a model to truly consider the interior. This would allow a complex spatial understanding to be developed by providing consideration for spatial transitions through the interior and aiding distance cognition, improving the experience of constructing a spatial cognitive map. It is important to acknowledge that people have different levels of spatial cognition and create cognitive maps differently. These differences are reinforced with the temporal nature of whiteout experiences informed by the level of spatial information provided and the complexity of user interface. The following conditions set out a framework to improve spatial cognition within digital architectural models:

Distance information

It is important to identify and aid distance cognition, by providing interior-aware transitions and spatially responsive wayshowing and pathways that can display distance information.

Building detail (not realism)

A high level of modelled detail directly relates to the comprehension of scale. A level-of-detail convention is required, similar to the conventions of two-dimensional working drawings.

Orientation indication

Aid the expression of orientation with a solid ground plane and rendered sky dome. Include the use of plan and map views to identify current orientation.

Location identification

Provide local information that is space sensitive, with the display of metadata such as room name, use, and size. Include the use of plans and maps in location identification.

Building Data

The ability to easily access all types of data spatially, beyond just building geometry, in a location-based and task-appropriate interface that combines navigation methods.

Architectural Design

Consideration of architectural design that provides clear wayshowing systems, which are often not well architecturally resolved, to improve wayfinding and navigation.

Implications

The adoption of the BIM processes continue to increase in the building industry and more people are accessing three-dimensional digital building information encompassing the complete building cycle from design to demolition. The way in which people comprehend complex building information beyond paper-based media is at the beginning of a new phase, as working drawings were over 300 years ago.

Being able to correctly understand a proposed building during every stage of the design process is complex and a learned skill, and is something with which clients and operators' commonly have little experience. Although three-dimensional models, which offer improved spatial readability compared with two-dimensional drawings, can be explored, they can still be misunderstood. During the construction phases of a building, it is critical that everyone is able to visualise at the same level.

Virtual reality has been a futuristic technology that has never fully reached its potential, and has commonly been characterised by restrictive investment in hardware and workflows, coupled with inadequate resolution, which can induce motion sickness. Although it is still not a disruptive technology, virtual reality has recently undergone great improvement, and with further research funding has the potential to radically change how people engage with digital architectural models. Increased access to virtual reality goggles requires improved navigation tools to leverage their potential.

Over the period of my candidature, powerful mobile devices have been introduced that are transforming how we interact with information. These devices are changing building construction processes, including being able to provide onsite access to building information. The devices are starting to be capable of recording three-dimensional space and of creating digital representations of the buildings that we inhabit, transforming the range of digital architectural models to which we have access. Project Tango uses a mobile device to track the environment around it and create a three-dimensional model, and is able to produce vast three-dimensional digital models. With the rapid development of affordable virtual reality head-mounted display systems, such as Oculus Rift, and wearable augmented reality headsets, such as Google Glass, the way we interface with digital architectural models is evolving. We need new methods of navigating increasingly information-rich digital models.

As our online experience has been refined with the use of systematic user analytics, and given also the emergence of retail and entertainment spatial analytics of people's interactions and movements through physical space, the possibility arises of user spatial analysis within the BIM process. Analytics should inform not only the refinement of architectural design but, also the tools we use to experience digital architectural models. The ways in which people learn to engage with digital architectural models is changing, with young children now able to create interactive digital building models, which was not even possible only a few years ago.

My research has revealed the importance of distance comprehension in spatial cognition, an area not well supported in three-dimensional digital models, along with how orientation and location awareness aid navigation. In addition, this study has shown how modelled detail aids spatial comprehension, helping to communicate and understand scale and architectural intent. Furthermore, it is the interface of the combination of all the methods and techniques of wayfinding, navigation, wayshowing, and pathfinding that will reduce the incidence of whiteout.

The framework can change the practice of all stages of complex building construction by improving spatial cognition during the design phases, allowing an accurate understanding of a proposed building design to allow better comprehension of construction processes including an improved user experience once the building is open. To allow this to happen requires a change in planning processes which would be confrontational for many people, requiring consideration of how different people experience a building during all phases of a building's life. Elements of the frame require an increase of computation power, higher detailed models and a broader range of building data will support improved spatial cognation. Other elements need new software interfaces to improve spatial cognition without hindering productivity.

Figure 5.0
Polar Plateau by Anne Noble (2009). Emerging from the whiteout, a person walking across the vast white surface of the Antarctic plateau, on a journey.

5 Conclusion

Navigation and spatial cognition in digital architectural models is still difficult, even after nearly 30 years of research. Limited sensorial outputs, restrictive tools, and minimal feedback contribute to the occurrence of disorientation or whiteout moments inside digital architectural models. By combining research from computer science and psychology, and using my background and experience as a spatial information architect, this exegesis sets out approaches for improving the ways in which people interface with digital architectural models.

Many explorers have navigated through 'whiteout' conditions by developing skills and tools to enable smooth travel. Methods of navigation and wayshowing in virtual environments are still being established. Typically, studies of navigation in virtual environments have simplified the spaces to simple two-dimensional extrusions. The complexity of large building information models requires such thinking to be extended.

Previous research, including the line of work established by Darken and Sibert (1993), has discussed many methods of improving navigation. My research adds to the discussion by providing a focus on aiding distance estimation, with a view to improving navigation via informative wayshowing to reduce moments of whiteout, without restricting the user's freedom to explore. The problems of spatial cognition of proposed buildings influence the construction and usability of the buildings, being affected by poorly designed wayshowing and navigation tools that do not orient or locate a user while providing a sense of scale.

My research has demonstrated that it is important to acknowledge that a broad range of conditions need to be continuously developed if spatial cognition within digital architectural models is to be improved. The richness of information in building information models will continue to increase (Eastman et al., 2011); however, as evidenced in my Distance projects, with this richness comes further complexity and thus an increased need to improve the ways for the navigator to interact with the information.

John Huth recognised that navigators have to deal with "spatial orientation, the ability to estimate distances and find position" (Huth, 2013, p. 8); these are still challenges, however, for navigators of digital models. My research suggests that by aiding distance comprehension and providing clear and informative wayshowing methods, spatial cognition for the navigator improves. There is still considerable work required in further developing these methods, but the framework established in my study provides the directions for that journey.

This framework for navigation tools and wayshowing strategies for improving spatial cognition within digital architectural models is my contribution to the advancement of knowledge in the field. To improve the experience of constructing a spatial cognitive map, navigation tools need to move beyond an objectification of the model to a complex spatial understanding. An effective route towards this improvement is by providing navigators greater consideration of the spatial transitions through the interior, and by aiding their capability for distance cognition.

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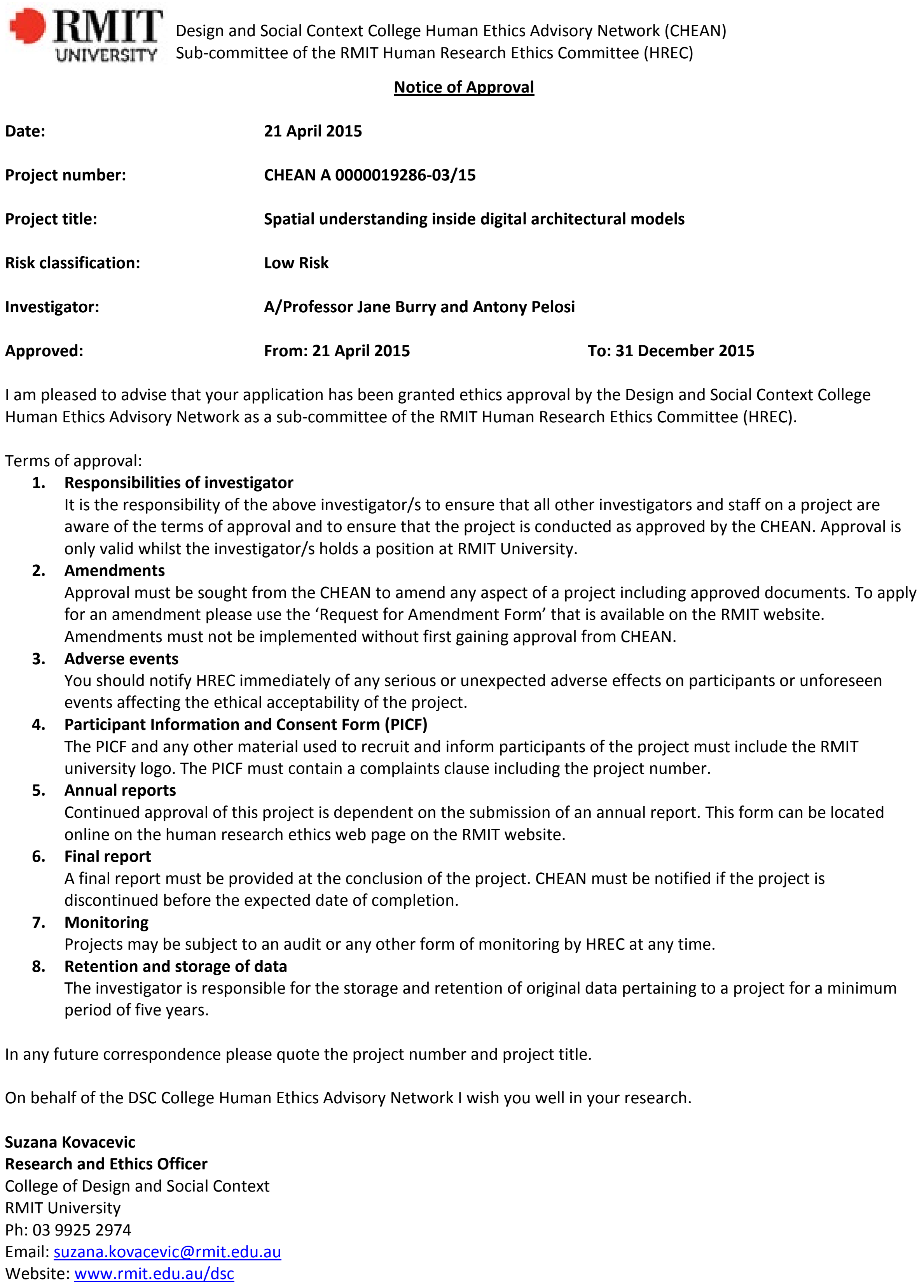
Illustration Credits

Appendix 1

Notice of ethics Approval.



Design and Social Context College Human Ethics Advisory Network (CHEAN)
Sub-committee of the RMIT Human Research Ethics Committee (HREC)

Notice of Approval

Date:	**21 April 2015**	
Project number:	**CHEAN A 0000019286-03/15**	
Project title:	**Spatial understanding inside digital architectural models**	
Risk classification:	**Low Risk**	
Investigator:	**A/Professor Jane Burry and Antony Pelosi**	
Approved:	**From: 21 April 2015**	**To: 31 December 2015**

I am pleased to advise that your application has been granted ethics approval by the Design and Social Context College Human Ethics Advisory Network as a sub-committee of the RMIT Human Research Ethics Committee (HREC).

Terms of approval:

1. **Responsibilities of investigator**
   It is the responsibility of the above investigator/s to ensure that all other investigators and staff on a project are aware of the terms of approval and to ensure that the project is conducted as approved by the CHEAN. Approval is only valid whilst the investigator/s holds a position at RMIT University.
2. **Amendments**
   Approval must be sought from the CHEAN to amend any aspect of a project including approved documents. To apply for an amendment please use the 'Request for Amendment Form' that is available on the RMIT website. Amendments must not be implemented without first gaining approval from CHEAN.
3. **Adverse events**
   You should notify HREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.
4. **Participant Information and Consent Form (PICF)**
   The PICF and any other material used to recruit and inform participants of the project must include the RMIT university logo. The PICF must contain a complaints clause including the project number.
5. **Annual reports**
   Continued approval of this project is dependent on the submission of an annual report. This form can be located online on the human research ethics web page on the RMIT website.
6. **Final report**
   A final report must be provided at the conclusion of the project. CHEAN must be notified if the project is discontinued before the expected date of completion.
7. **Monitoring**
   Projects may be subject to an audit or any other form of monitoring by HREC at any time.
8. **Retention and storage of data**
   The investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

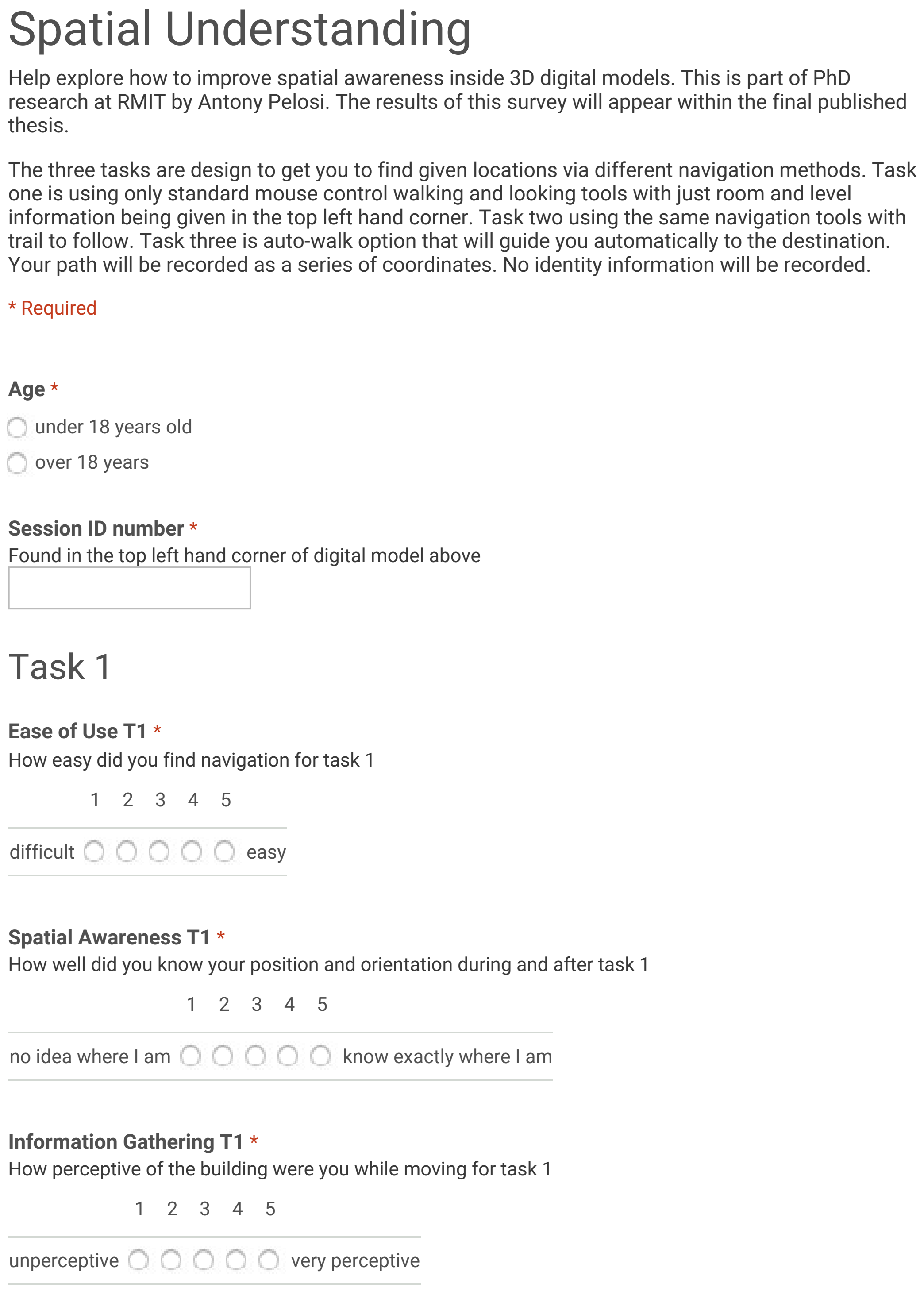
In any future correspondence please quote the project number and project title.

On behalf of the DSC College Human Ethics Advisory Network I wish you well in your research.

Suzana Kovacevic
Research and Ethics Officer
College of Design and Social Context
RMIT University
Ph: 03 9925 2974
Email: suzana.kovacevic@rmit.edu.au
Website: www.rmit.edu.au/dsc

Appendix 2

Questionnaire used in Te Ara Hihiko project.



Spatial Understanding

Help explore how to improve spatial awareness inside 3D digital models. This is part of PhD research at RMIT by Antony Pelosi. The results of this survey will appear within the final published thesis.

The three tasks are design to get you to find given locations via different navigation methods. Task one is using only standard mouse control walking and looking tools with just room and level information being given in the top left hand corner. Task two using the same navigation tools with trail to follow. Task three is auto-walk option that will guide you automatically to the destination. Your path will be recorded as a series of coordinates. No identity information will be recorded.

* Required

Age *

○ under 18 years old

○ over 18 years

Session ID number *

Found in the top left hand corner of digital model above

Task 1

Ease of Use T1 *

How easy did you find navigation for task 1

	1	2	3	4	5	
difficult	○	○	○	○	○	easy

Spatial Awareness T1 *

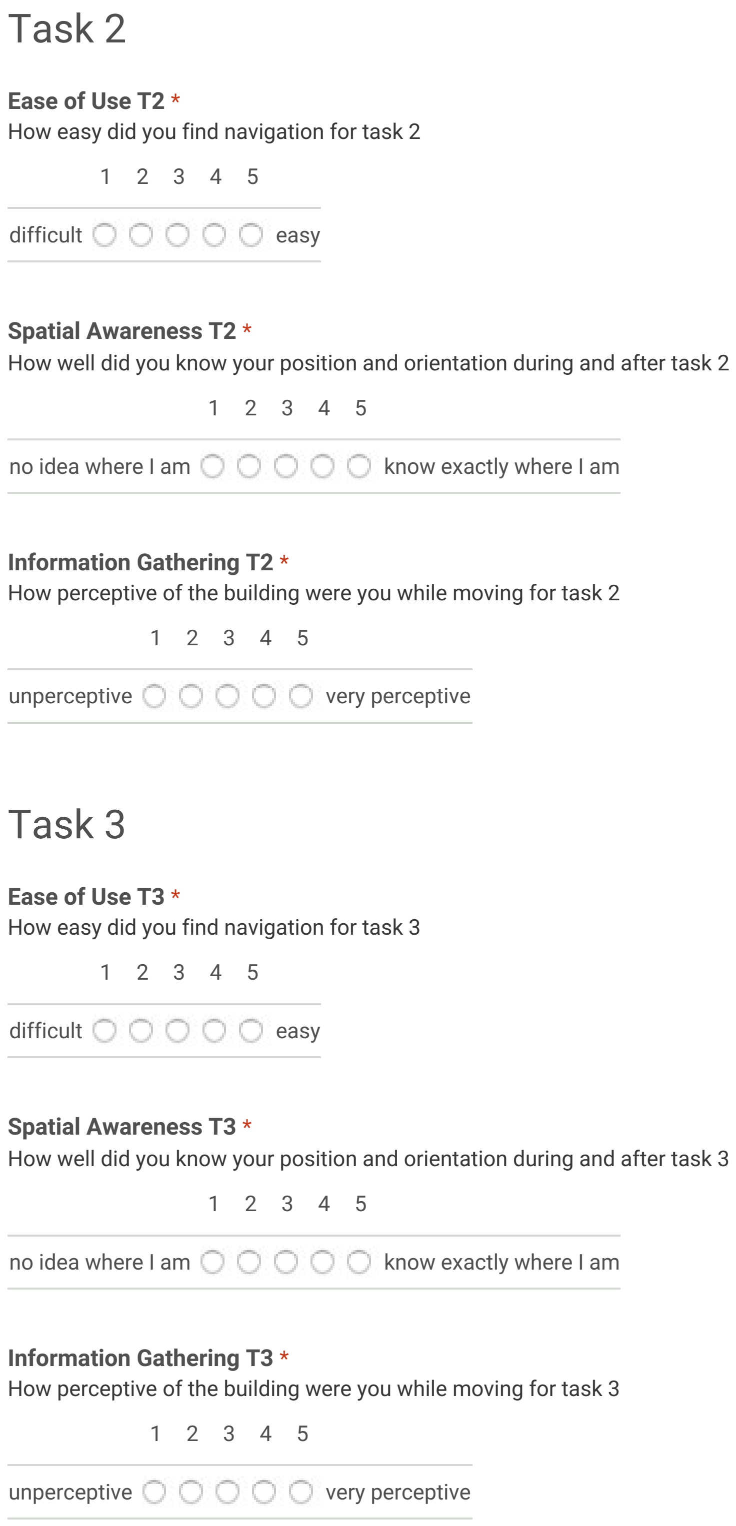
How well did you know your position and orientation during and after task 1

	1	2	3	4	5	
no idea where I am	○	○	○	○	○	know exactly where I am

Information Gathering T1 *

How perceptive of the building were you while moving for task 1

	1	2	3	4	5	
unperceptive	○	○	○	○	○	very perceptive



Task 2

Ease of Use T2 *

How easy did you find navigation for task 2

	1	2	3	4	5	
difficult	○	○	○	○	○	easy

Spatial Awareness T2 *

How well did you know your position and orientation during and after task 2

	1	2	3	4	5	
no idea where I am	○	○	○	○	○	know exactly where I am

Information Gathering T2 *

How perceptive of the building were you while moving for task 2

	1	2	3	4	5	
unperceptive	○	○	○	○	○	very perceptive

Task 3

Ease of Use T3 *

How easy did you find navigation for task 3

	1	2	3	4	5	
difficult	○	○	○	○	○	easy

Spatial Awareness T3 *

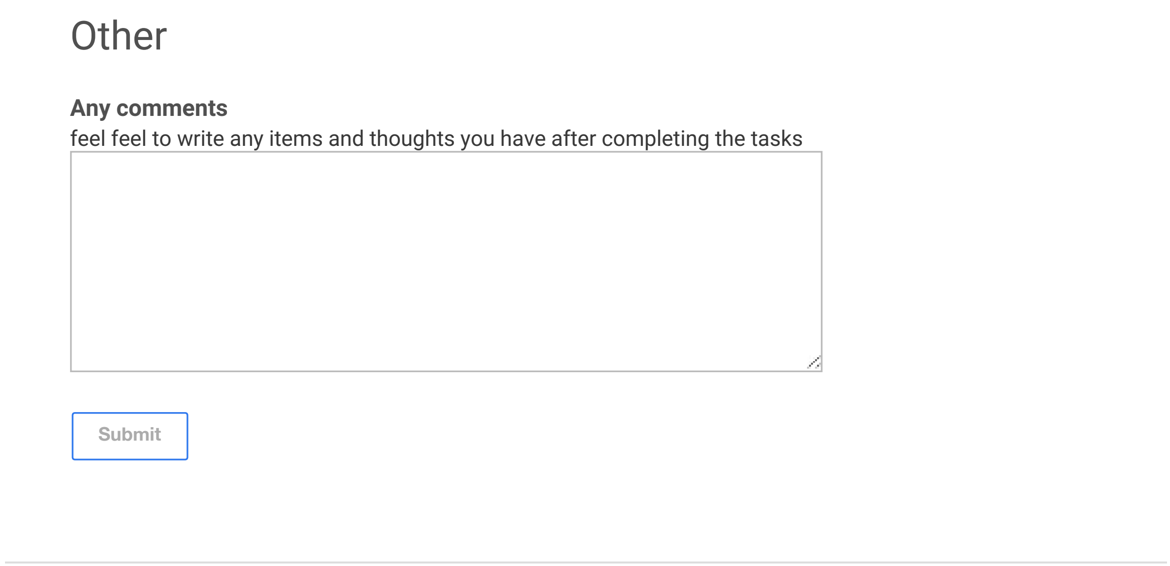
How well did you know your position and orientation during and after task 3

	1	2	3	4	5	
no idea where I am	○	○	○	○	○	know exactly where I am

Information Gathering T3 *

How perceptive of the building were you while moving for task 3

	1	2	3	4	5	
unperceptive	○	○	○	○	○	very perceptive



Other

Any comments
feel feel to write any items and thoughts you have after completing the tasks

Appendix 3

Tabulated results from Te Ara Hihiko project.

Participant	Task 1				Task 2				Task 3			
	Ease of Use	Spatial Awareness	Information Gathering	Time (min:sec)	Ease of Use	Spatial Awareness	Information Gathering	Time (min:sec)	Ease of Use	Spatial Awareness	Information Gathering	Time (min:sec)
1	2	3	2	01:01	3	4	4	01:24	5	4	5	00:48
2	3	3	4	04:28	3	4	4	01:20	5	4	4	00:49
3	3	3	4	02:11	4	4	4	01:15	5	3	3	00:47
4	3	4	5	00:56	5	5	4	01:21	5	3	3	00:50
5	1	1	2	01:05	5	2	3	01:04	5	3	2	00:56
6	1	4	4	01:17	2	2	2	01:51	5	3	2	00:48
7	3	5	5	04:18	4	3	2	01:32	5	5	4	00:51
8	2	4	3	12:59	5	5	5	02:06	5	5	5	00:50
9	1	4	3	02:50	4	4	4	01:35	5	3	4	00:48
10	1	3	4	02:15	3	3	4	00:53	5	2	2	00:49
11	3	4	4	01:37	4	4	4	01:09	5	5	5	00:48
Average	2	3	4	03:11	4	4	4	01:25	5	4	4	00:49

Participant	Comments
1	The wayfinding of the actual building was very confusing e.g the Level D, E Typography on the the ceiling.
2	No Comment
3	The interaction with the mouse felt limited. If the cursor left the view then movement would cease, however there was no indication of how close to full speed the camera was moving. The Mouse only movement was tricky, too, as I am far more used to a gaming style wasd+mouse movement approach. This allows for movement of the camera with panning left/right at the same time as moving forward and back and rotating the camera itself.

4	I am surprised by my own results, I expected to be more perceptive of the space when being led to the task but actually it was the opposite: I now have a better understanding of the first task but little idea of how to get to the last one. It's like driving in a new city versus being driven, the former will give you a good idea while the latter gives you little idea of how to get around. As I see it, perception tools like compass (to know direction), room and level information and grid reference will be most helpful in understanding the place. A "radar" mode like in shoot-em-up games would be useful too to understand the space.
5	Some observations: The actual act of moving around the model was difficult. It was also tiresome. Look to modern video games for better movement mechanics/controls. Having said that, 3D navigation on a 2D screen is always going to be difficult. There just not enough visual cues, especially our peripheral vision is not engaged at all, therefore we miss out on the feeling of scale and space. There was no or very little collision detection in the model. This lack severely impacts on ease of navigation. Falling off into a ditch is just not nice. If self-navigation through a model is very important then make sure that the person asked to navigate can do it comfortably. I find it obvious that the level of difficulty in performing this task will have a negative effect on my perception of the building/model and spacial awareness. The model was also lacking its contextual setting. While I know the building it was not immediately obvious where I was. I was asked to perform a task which I would perform very differently in the physical world. First of all I would look for cues as to where the entrance might be. The model (geometry + lighting + textures) does not present that information very well, in my opinion. Having found there door I would then look for some kind of site map and use it to determine a path to my destination. I propose that a visual introduction to the model would help a lot in developing spacial awareness and improve results of subsequent navigation oriented tasks. For example, the user could be shown a high level fly-over of the entire model before being placed at the staring point (see https://www.youtube.com/watch?v=tO5a6_mxKzs) I'll be happy to answer more questions.
6	This was actually my second attempt. in my first attempt it took me a while to work out the Walk function so a was stuck outside trying to move. Once I'd worked that out and found my way to Room D and started the second task I walked into a wall and couldn't back out and inadvertently clicked on a Bookmark at the top of the Chrome window which obviously opened the new page leaving me to start all three tasked again, making the tasks somewhat easier.
7	how about some weapons?
8	The difficulty in Task 1 is not the navigation controls itself but identifying what you are looking for in order to find the route required. in reality a building like this would have (hopefully) clear signage directing where to go which is missing in the virtual building used here. Perhaps that's the point of the exercise?? Task 2 easy because you a following a clearly marker path with the blue line. Task 3 required no operator interaction at all.
9	No Comment
10	Navigation was not initially intuitive, spent the first minute using arrow keys to try to make me move until I realised I needed to use mouse for walking direction and movement.
11	No Comment